OBSERVATION REQUIREMENTS FOR UNMANNED PLANETARY MISSIONS

North American Rockwell
Anaheim, California

11 March 1970

CR 73458 AVAILABLE TO THE PUBLIC

SD 70-24

OBSERVATION REQUIREMENTS FOR UNMANNED PLANETARY MISSIONS

11 March 1970

Contract NAS2-5647

Approved by

A. C. Jones
Program Manager

Space Division
North American Rockwell

PRECEDING PAGE BLANK NOT FILMED.

FOREWORD

This report presents the results of a top-down study in which the goals and objectives of future planetary missions are defined. Specifically, it establishes the scientific and engineering objectives for exploration of the outer planets. It further defines the observable phenomena and parameters suitable for remote sensing. The information reported herein is part of an overall program to (1) establish the scientific and engineering knowledge and observation requirements for planetary exploration in the 1975 to 1985 time period, (2) define the state of the art and expected development of instrument systems appropriate for remote sensing of planetary environments, (3) establish scaling laws relating performance and support requirements of candidate remote sensor systems, (4) establish fundamental remote sensor system capabilities and limitations during encounter and other dynamical conditions for specific missions, and (5) construct families of candidate remote sensors compatible with selected missions.

This study was performed for NASA, Office of Advanced Research and Technology, Mission Analysis Division, by the Space Division (SD) of North American Rockwell Corporation (NR) as part of Contract NAS2-5647.

To achieve these goals, a multi-part program was initiated. Part I considered the support requirements for orbital imaging of the inner planets (Mercury, Venus, Mars) and Jupiter, and was accomplished under Contract NAS2-4494 by Illinois Institute of Technology Research Institute (IITRI) (Reference 1). Part II, which is being conducted by Space Division of North American Rockwell Corporation, extends this effort to include nonimaging sensor systems for the inner and outer planets, plus imaging sensor systems for the outer planets.

The Part II effort is conducted in three sequential phases. Phase 1 (covered in this report) establishes the scientific and engineering objectives and observation requirements. Phase 2 will deal with definition of candidate remote sensors and the development of scaling laws that relate sensor measurement capabilities to support requirements, corresponding to the goals and objectives. Phase 3 will establish families of remote sensors compatible with selected missions.

ACKNOWLEDGEMENTS

This report was prepared by A. C. Jones, Program Manager, and Dr. J. B. Weddell, Phase 1 Project Manager. Other personnel participating were Dr. M. Blander, D. G. Brundige, Dr. J. W. Haffner, Dr. G. M. Hidy, Dr. W. W. Ho, C. D. Martin, A. H. Marks, and W. F. McQuillan. Professors R. E. Newell and G. deVaucouleurs served as consultants.

CONTENTS

*Bound separately

ILLUSTRATIONS

TABLES

GLOSSARY

The following terms used in this report are defined to avoid misunderstanding:

Engineering Knowledge Requirement. One related to the conduct of a mission or the improvement of technology.

Flyby. A parabolic or hyperbolic trajectory which enters the sphere of influence of a planet, but does not enter the atmosphere or reach the surface.

Goal. A broad purpose of the space program or of planetary exploration, e.g., the acquisition of scientific knowledge.

Imaging Sensor. One which produces two- or three-dimensional images of a planetary atmosphere or surface (or portion thereof), in response to electromagnetic radiation of any wavelength.

In Situ Sensor. One used in experiments related only to the local sensor environment.

Inner Planets. Mercury, Venus, Earth, and Mars.

Knowledge Requirement. A general and fundamental question concerning natural processes or technology.

Measurement. The acquisition of quantitative data concerning an environment or observable, e.g., the angular diameter of the visible disk of a planet.

Measurement Requirement. A quantitative description of the nature, quantity, and quality of measurements to satisfy an observation requirement.

Mission. The operations and trajectory of a space flight.

Objective. A specific purpose of planetary exploration, the attainment of which involves satisfaction of various knowledge requirements, e.g., understanding the origin and evolution of the solar system.

Observable. A property of a planet or planetary environment that can be defined in terms of physical measurements, e.g., the radius of a planet.

Observation Requirement. A quantitative description of the nature, quantity, and qualify of information to be obtained regarding an observable.

Outer Planets. Jupiter, Saturn, Uranus, Neptune, and Pluto.

Remote Sensor. An instrument which senses electromagnetic radiation, or electric, magnetic, or gravitational fields, originating at a point or region not in contact with the instrument.

Scaling Law. A graphical or functional relationship of a sensor support requirement to a measurement capability. A scaling law may involve trajectory parameters and other support requirements or aspects of measurement capability. It is based on characteristics of existing, developmental, or projected sensors.

Scientific Knowledge Requirement. One related to the knowledge of nature, for the sake of the knowledge.

Sensor. An instrument, or part thereof, that responds directly to an environment or to incident radiation.

Support Requirements. The characteristics of a sensor and operations related to its use in an experiment which impose demands on a spacecraft; e.g., mass, input power, output data rate and format, pointing stability, etc.

1.0 INTRODUCTION

1.1 PROGRAM OBJECTIVES

Exploration of the planets of our solar system is a major objective of our national space program. Through this exploration, scientists are addressing themselves to the two major scientific questions of our time; What is the origin of the solar system, and what is the origin and nature of life? Further, the engineering community is concerned with the development of space and Earth-based systems with operational procedures to perform useful research and services in space. This study is part of a continuing effort being performed by NASA for planning and ultimate accomplishment of these objectives.

A major task in the planning of future space missions and in the conceptual design of spacecraft is the definition of experiment payloads. The mission analyst and vehicle designer need to know the scientific and engineering observation requirements appropriate to the mission, the characterisitcs of candidate experiment sensors, their support subsystems and operations necessary to accomplish the observations. A program to develop this information for unmanned planetary flyby and orbiter missions has been intiated by the Mission Analysis Division (MAD) of the Office of Advanced Research and Technology (OART), National Aeronautics and Space Administration (NASA).

The overall goals of this program are to (1) establish the scientific and engineering knowledge and observation requirements for planetary exploration in the 1975 to 1985 time period, (2) define the state of the art and expected development of instrument systems appropriate for remote sensing of planetary environments, (3) establish scaling laws relating performance and support requirements of candidate remote sensor systems, (4) establish fundamental remote sensor system capabilities and limitations during encounter and other dynamical conditions for specific missions, and (5) construct families of candidate remote sensors compatible with selected missions.

Specifically, this report directs itself to the first goal identified above as Phase I of the overall program. The remaining program goals identified above will be studied in Phases II and III and reported separately.

1.2 PHASE I OBJECTIVES

One specific objective of this study phase, reported herein, is to define the scientific and engineering objectives for exploration of the outer planets, Saturn, Uranus, and Neptune.

The next objective is to identify observable phenomena and parameters suitable to remote sensing by imaging and nonimaging techniques that will provide useful information toward satisfying the exploration goals and objectives. In addition, nonimaging remote observation requirements will be defined for the inner planets and Jupiter. These objectives were achieved by members of NR's scientific staff and consultants in applicable scientific disciplinary areas. To simplify and standardize the data generated in this study, computer techniques are employed which are designed to be compatible with the development of system requirements, support requirements definition, documentation, processing, and mission analysis tasks to be performed in Phases 2 and 3.

2.0 SUMMARY

The goal of the effort reported here is to establish the observation requirements appropriate to unmanned planetary exploration in the 1975 to 1985 time period. These observations must support scientific and engineering knowledge requirements concerning planetary environments and properties. Consideration is limited to observations that can, in principle, be performed by remote sensors on flyby and orbiter spacecraft. In later phases of this study, the sensors to perform the observations will be defined and the sensor support requirements will be evaluated. Finally, families of sensors compatible with various planetary missions will be defined. Imaging observations of the inner planets and Jupiter have been described under Contract NAS2-2294.

A top-down approach began with definition of the scientific and engineering goals of planetary exploration, and proceeded through the increasingly specific and quantitative stages of knowledge requirements, observation objectives, observable properties, and observation and measurement requirements. At each stage, branches of the definition process were abandoned when they clearly were not appropriate to remote sensing on unmanned planetary flyby or orbiter spacecraft. The measurement capabilities of sensors and the support capabilities of spacecraft systems were not considered in this phase. The observation objectives and requirements were defined by consultant scientists and by appropriate specialists at the NR Space Division and NR Science Center.

The quantitative and verbal descriptions of observation requirements are documented by a data storage and retrieval computer program which gives visibility to the relationships among planetary exploration goals, knowledge requirements, and observation requirements. The estimated worth of attaining various values of each significant observation parameter (e.g., wavelength, spatial resolution) is also displayed.

The most important knowledge requirements relevant to the study objectives concern planetary interior structure, surface composition and topography, and atmospheric composition and meteorology. Visible imagery of outer planet cloud formations, and microwave, infrared, and visible spectrometry and radiometry of radiation absorbed or emitted by all planetary atmospheres, provide the most significant support to the knowledge requirements.

3.0 METHODOLOGY

3.1 DETERMINATION OF OBSERVATION REQUIREMENTS

3.1.1 Top-Down Approach

A balanced and comprehensive experimental program in any space mission or group of missions is best achieved by a morphological or top-down approach in which the goals of the national space program provide a framework for the definition of scientific and engineering objectives, i.e., questions of a broad and fundamental nature to which answers may be sought through space exploration and operations. Figure 1 shows that the scientific goals (related to the desire for knowledge) and the engineering operational goals (related to the attainment of capabilities in space and the exploitation of these capabilities) imply partially overlapping data requirements. A given experiment, therefore, may contribute to the attainment of both classes of goals.

The definition of fundamental scientific and engineering space exploration objectives and the assignment of priorities to these objectives are essentially value judgments. By a scientific objective is meant a question of broad scope, of basic interest to the scientific community for the sake of the answer itself, which may in principle be sought through investigation of space and celestial objects. Objectives and experiments related to Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune are of interest here.

The determination of scientific payload requirements begins with recognition of the national goals of the space program and the corresponding planetary exploration objectives. These goals are the advancement of scientific knowledge, the building of a civilian technological base, the advancement of capabilities for space flight, and the enhancement of national prestige. To attain these objectives, investigations must be carried out which, regardless of their motivation in terms of national goals, can usually be categorized within one or more of the fundamental science disciplines. For example, the quantitative requirements for atmospheric circulation measurements may be different from the scientific and spacecraft engineering standpoints, but the measurement discipline involved is that of meteorology in both cases.

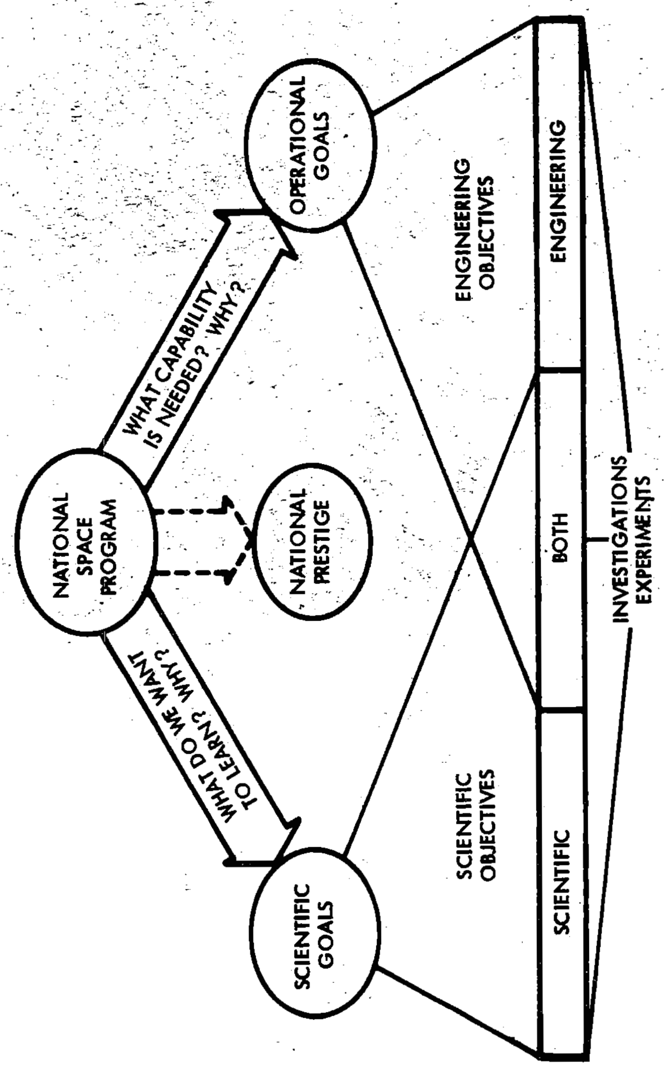

Figure 1. Space Exploration Goals and Objectives

Space Division
North American Rockwell

Experiments, which can be defined in each investigation area, consist not only of the sensor instrumentation but also of support equipment and the mission operations required to conduct the experiment and return the data to Earth. Phases 2 and 3 of this study will be concerned with sensors, their support requirements, and their compatibility with various missions. We will only determine what demands must be satisfied by support equipment, and will not define this equipment. Consideration of compatibility will be limited to the ability of a sensor within the state of art corresponding to the mission launch date (or, rather, the experiment selection date), to obtain desired data during a specified mission. Spacecraft integration problems and payload constraints will not be considered except to point out potential cases of mutual interference among sensors identified as members of a compatible family.

The levels of organizational relationship among space objectives, programs, and experiments are illustrated in Figure 2. This figure traces national space goals (e.g., increasing scientific knowledge) down to specific experiments (e.g., a measurement of the infrared radiation flux emitted by the Saturn atmosphere) through intermediate levels of problem areas, scientific objectives, disciplinary areas, and investigations such as atmospheric temperature. Figure 2 also relates experiment sensors to vehicle types and missions with which they may be compatible, and then to mission categories and broad space program areas.

Table 1 summarizes the levels of development of observation requirements in the top-down approach, and identifies places in this report where the elements at each level are defined. As each level is discussed, an example of the connection between that level and the next is given. This set of examples leads to a specimen of the detailed tabulation (Table 2) of quantitative observation parameters.

Table 1. Levels in Top-Down Approach

Level	Name	Location
1	Goal	Section 4.1
2	Knowledge requirement	Tables 3 and 4
3	Observation objective	Tables 6 and 7
4	Observable	Tables 8 and 9

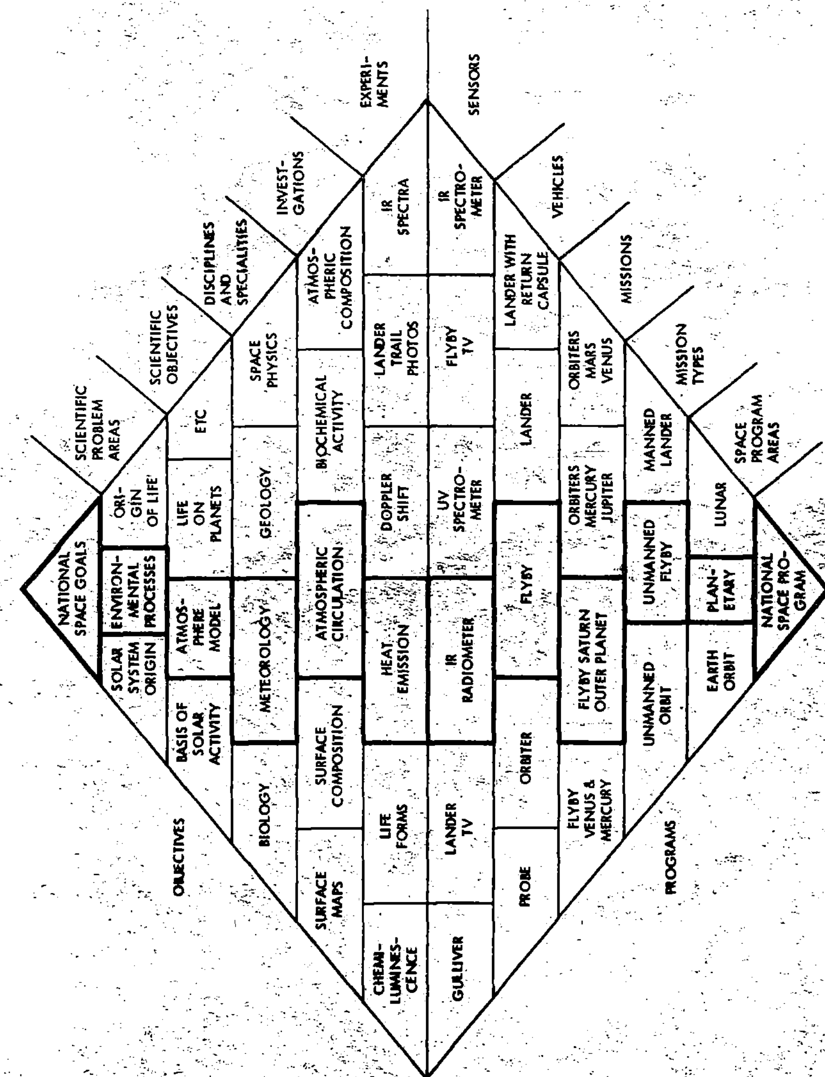

Figure 2. Space Objectives and Programs

3.1.2 Reference Source Material

The National Academy of Sciences Space Science Board (NAS-SSB) has in the past five years published three major reports concerning the scientific objectives of the space program. In the first report (Reference 2), the NAS-SSB listed three general scientific problem areas to which the national space program should be addressed:

1. The origin and evolution of the solar system and the universe

2. The origin and evolution of life

3. The nature of the dynamic processes that shape the terrestrial environment.

This report defined and ranked in importance several objectives of exploration of the moon, the planets and their satellites, the asteroids, and interplanetary space, the fulfillment of which will shed light on these problem areas. Numerous detailed questions, corresponding to specialized investigations, were presented to indicate an orderly approach to attainment of the objectives.

The second report (Reference 3) was concerned with planetary investigations which might reasonably be carried out in the 1968-1975 time period, and so was limited mainly to the unmanned exploration of Mercury, Venus, and Mars.

Of greatest importance to this study is Reference 4, which reaffirms the general objectives mentioned, points out the importance of the outer planets and interplanetary space at great distances from the Sun, discusses several investigation areas, and recommends several planetary mission types and experiments as well as Earth-based observations. The NAS-SSB here recognized the fortunate coincidence of adequate launch vehicles and spacecraft technology, with rare opportunities to use gravity-assisted flybys to encounter several outer planets on single flights of much shorter duration than direct missions to Saturn and beyond.

In addition to the NAS-SSB reports, numerous planetary exploration studies (References 5, 6 and 7) have provided much information on knowledge and observation requirements applicable to the present program.

3.1.3 Participation by Consultants

The NAS-SSB and other external recommendations were translated into specific observation and measurement requirements with the assistance of:

Professor Gerard de Vaucouleurs, Department of Astronomy, University of Texas

Professor Reginald E. Newell, Department of Meteorology, Massachusetts Institute of Technology

Professor de Vaucouleurs concerned himself mainly with the requirements of imaging, radiometric, and spectrometric measurements of the outer planets. Professor Newell concentrated on observation requirements bearing on the circulation and energy balance of the outer planets' atmospheres. The consultant efforts were coordinated by Dr. J. B. Weddell, with the assistance of the NR Science Center staff. The consultants' reports are reproduced verbatim in Appendix B. Their significant recommendations are incorporated in Sections 4 and 5, and in the observation requirements data presented in Appendix C.

3.2 AUTOMATED DOCUMENTATION

It was apparent at the outset of the study that a large quantity of observation requirements data would be generated. It would become necessary (1) to display these data compactly, economically, and in a uniform format; (2) to process the data in a way conducive to a minimum of preparation effort and to automatic sequencing of cases; (3) to display the limiting (i.e., most stringent) observation requirements common to a set of cases from which a compatible family of sensors may later be constructed; and (4) to correlate the data with sensor scaling law and mission trajectory information in Phases 2 and 3. It was decided, therefore, to adopt an Observations Requirements Data Sheet (ORDS) to record the requirements, and to prepare a computer program, Space Experiments Requirements Analysis (SERA) to convert the ORDS into self-explanatory tabular presentations.

3.2.1 Observation Requirements Data Sheet

The ORDS provides for entry of the following kinds of information:

1. The goal and knowledge requirement supported by a given observation objective; if several goals and/or knowledge requirements are supported, other combinations can be listed on separate forms.

2. The worth or value w_k on a scale of 0 to 1, of the support of the k^{th} observation objective to the indicated goal-knowledge requirement combination.

3. The observable property associated with the objective, the related observation type (i.e., general type of sensor), and the worth $w_{j\ell}$ of determining the j^{th} observable property at the ℓ^{th} planet. Other observable properties, observation types, planets, and corresponding values of $w_{j\ell}$, may be entered on separate forms.

4. Each observation parameter a_i (e.g., longest wavelength) relevant to the observation requirement is defined as follows:

   a. Worth w_i (a_i) of attaining value $a_i = a_i'$.

   b. "Best" or most stringent desired measurement capability a_i'; if a_i is better than a_i', w (a_i) = w (a_i').

   c. "Worst" or least stringent acceptable capability a_i''; if a_i is poorer than a_i'', w $(a_i) = 0$.

   d. Functional form of w_i (a_i) for values of a_i between a_i' and a_i''. The allowed functional forms are described in Section 5.3.1 and in Appendix D.

5. Explanatory remarks (not processed by computer program).

Figure 3 is an example of a completed ORDS. Detailed instructions for preparing the ORDS are included in Appendix D. The example is discussed in Section 5.3.2.

3.2.2 Summary of Computer Program

The SERA computer program is envisioned as a set of routines to process the information contained in the ORDS, display it in an understandable format, similarly process and display information related to sensor capabilities and support requirements and mission trajectories, and correlate these data to calculate and display portions of the study results in Phases 2 and 3. In Phase 1, only the first module (SERA-1) of SERA, dealing with the ORDS information alone, has been developed. The SERA-1 program reads punched cards containing the ORDS data and libraries of names of goals, knowledge requirements, and the like, as well as certain program control and option selection parameters. The output for the case represented by the ORDS in Figure 3 is illustrated in Table 2. This example is developed in stages at each level of the top-down approach. The output is in two parts, the ORDS information itself and the most stringent value of each observation parameter associated with a specified subset of ORDS.

The observation objective and observable property descriptions entered in the ORDS, as in Figure 3, need not be the same as the SERA-1 library titles corresponding to the observation objective and observable property numbers. The use of other descriptions allows more precise definition of the purpose and nature of an observation than the library titles permit.

The program also calculates the products $(w_R\, w_{i\ell})$ and $(w_i\, w_{j\ell})$. Appendix D, a user's manual for SERA-1, contains a listing, load module map, data preparation and execution instructions, and specimen data and results. Source and object decks are transmitted separately.

PLANETARY OBSERVATION REQUIREMENTS DATA SHEET

Space Division
North American Rockwell

DECK ______ PROGRAMMER ______________ DATE SUBMITTED ___/___/19__ PAGE ____ OF ____ JOB ________

GOAL	KNOWL.	(k) OBJECT.	OBJECT. WORTH	OBSERVATION OBJECTIVE	IDENTIFICATION
1	4	13	.85	NEUTRAL, IØN, ELECTRØN DENSITY PRØFILES IN ATMØSPHERE	13320551
				OBSERVATION OBJECTIVE (CONT)	2
				OBSERVATION OBJECTIVE (CONT)	3

(j) OBSERV.	OBSERV. TYPE	(l) PLANET	OBSERV. WORTH	OBSERVABLE PROPERTY	IDENTIFICATION
32	36	5	.85	BI-FREQUENCY RADIØ ØCCULTATIØN (ATTENUATIØN, PHASE SHIFT)	13320554

OBSERVABLE PROPERTY (CONT)	i16	i17	i18	i19	i20	IDENTIFICATION
	38	39	16	20		13320555

	WORTH	WORST	BEST	F
LONGEST λ (μ)	.7	7505	1706	3
SHORTEST λ (μ)	.7	1305	3504	3
SPECTRAL RESOLUTION (μ)	.			
SPATIAL RESOLUTION (M)	.			
FRACTION COVERED	.			
IDENTIFICATION	13320556			
N LATITUDE (DEG)	.5	0000	9001	2
S LATITUDE (DEG)	.5	0000	9001	2
MAX. SUN ANGLE (DEG)	.4	9031	9001	2
MIN. SUN ANGLE (DEG)	.4	9001	9031	2
VERTICAL RESOLUTION (M)	.			
IDENTIFICATION	13320557			
MAX. ALTITUDE (M)	.			
MIN. ALTITUDE (M)	.			
NUMBER OF SAMPLES	.			
DURATION OF 1 SAMPLE (SEC)	.			
SAMPLING INTERVAL (SEC)	.9	1000	1052	1[illegible]
IDENTIFICATION	13320558			
i16	.9	1802	1001	14
i17	.6	1802	4501	12
i18	.9	2600	2601	14
i19	.8	3602	3601	11
i20	.			
IDENTIFICATION	13320559			

REMARKS Also goals 3, 5. For goal 5, objective worth = 0.99
Also planets. 1, 2, 4, 6, 7, 8.

REFERENCE Hidy, Martin

COMPILER Weddell DATE 12/23/1969

Figure 3. Planetary Observation Requirements Data Sheet

Table 2. Example of Observation Requirements

```
*** PLANETARY OBSERVATION OBJECTIVES AND REQUIREMENTS ***

OBSERVATION OBJECTIVE 13. ATMOSPHERIC TEMPERATURE, PRESSURE, DENSITY DISTRIBUTIONS

GOAL 1 UNDERSTAND ORIGIN AND EVOLUTION OF UNIVERSE AND SOLAR SYSTEM.

KNOWLEDGE REQUIREMENT 4 WHAT ARE THE PHYSICAL AND CHEMICAL PROPERTIES OF PLANETARY ATMOSPH.
  VS. ALTITUDE, ON GLOBAL AND LOCAL BASES. WHAT IS THE ROLE OF TRACE SUB-
  STANCES IN DETERMINING ATMOSPHERIC PROPERTIES AND VEHICLE PERFORMANCE.

OBJECTIVE WORTH = 0.85

OBSERVABLE PROPERTY 32. ELECTROMAGNETIC SIGNAL TIME AND RAY REFLECTION.

OBSERVATION TECHNIQUE 36. EARTH OCCULTATION (RADIO)
 PLANETARY BODY 5. JUPITER
 OBSERVATION WORTH. GROSS WORTH = 0.85, NET WORTH = 0.72
  OBSERVATION PARAMETER 1. LONGEST WAVELENGTH OF SPECTRAL BAND (MICRONS)
   DESIRED MEASUREMENT CAPABILITY = 0.170E 07. WORTH AT D.M.C. GROSS WORTH = 0.70, NET WORTH = 0.51
   MINIMUM MEASUREMENT CAPABILITY = 0.750E 06.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 3, EXPONENTIAL
  OBSERVATION PARAMETER 2. SHORTEST WAVELENGTH OF SPECTRAL BAND (MICRONS)
   DESIRED MEASUREMENT CAPABILITY = 0.350E 05. WORTH AT D.M.C. GROSS WORTH = 0.70, NET WORTH = 0.51
   MINIMUM MEASUREMENT CAPABILITY = 0.170E 05.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 3, EXPONENTIAL
  OBSERVATION PARAMETER 6. NORTHERNMOST LATITUDE OF AREA TO BE COVERED (DEGREES)
   DESIRED MEASUREMENT CAPABILITY = 0.900E 02. WORTH AT D.M.C. GROSS WORTH = 0.50, NET WORTH = 0.36
   MINIMUM MEASUREMENT CAPABILITY = 0.0
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 2, SINUSOID
  OBSERVATION PARAMETER 7. SOUTHERNMOST LATITUDE OF AREA TO BE COVERED (DEGREES)
   DESIRED MEASUREMENT CAPABILITY = 0.900E 02. WORTH AT D.M.C. GROSS WORTH = 0.50, NET WORTH = 0.36
   MINIMUM MEASUREMENT CAPABILITY = 0.0
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 2, SINUSOID
  OBSERVATION PARAMETER 8. MAXIMUM SUN ELEVATION ANGLE ABOVE HORIZON AT REGION OBSERVED (DEGREES)
   DESIRED MEASUREMENT CAPABILITY = -0.900E 02. WORTH AT D.M.C. GROSS WORTH = 0.40, NET WORTH = 0.29
   MINIMUM MEASUREMENT CAPABILITY = -0.900E 02.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 2, SINUSOID
  OBSERVATION PARAMETER 9. MINIMUM SUN ELEVATION ANGLE ABOVE HORIZON AT REGION OBSERVED (DEGREES)
   DESIRED MEASUREMENT CAPABILITY = -0.900E 02. WORTH AT D.M.C. GROSS WORTH = 0.40, NET WORTH = 0.29
   MINIMUM MEASUREMENT CAPABILITY = 0.900E 02.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 2, SINUSOID
  OBSERVATION PARAMETER 15. INTERVAL BETW. COMMENCEMENT OF TWO SUCCESSIVE SAMPLE ACQUIS. PDS. (SEC)
   DESIRED MEASUREMENT CAPABILITY = 0.100E-01. WORTH AT D.M.C. GROSS WORTH = 0.90, NET WORTH = 0.65
   MINIMUM MEASUREMENT CAPABILITY = 0.100E 01.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 11, LINEAR, LOG10(ARGUMENT)
  OBSERVATION PARAMETER 16. INTENSITY RESOLUTION (GRAY SCALE,ETC.)(PERCENT OF MAXIMUM INTENSITY)
   DESIRED MEASUREMENT CAPABILITY = 0.260E 01. WORTH AT D.M.C. GROSS WORTH = 0.90, NET WORTH = 0.65
   MINIMUM MEASUREMENT CAPABILITY = 0.260E 02.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 14, TRUNCATED EXPONENTIAL, LOG10(ARGUMENT)
  OBSERVATION PARAMETER 20. PHASE SHIFT (DEGREE)
   DESIRED MEASUREMENT CAPABILITY = 0.360E 02. WORTH AT D.M.C. GROSS WORTH = 0.80, NET WORTH = 0.58
   MINIMUM MEASUREMENT CAPABILITY = 0.360E 03.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 11, LINEAR, LOG10(ARGUMENT)
  OBSERVATION PARAMETER 38. LATITUDE INTERVAL (DEGREES)
   DESIRED MEASUREMENT CAPABILITY = 0.100E 02. WORTH AT D.M.C. GROSS WORTH = 0.90, NET WORTH = 0.65
   MINIMUM MEASUREMENT CAPABILITY = 0.180E 03.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 14, TRUNCATED EXPONENTIAL, LOG10(ARGUMENT)
  OBSERVATION PARAMETER 39. LONGITUDE INTERVAL (DEGREES)
   DESIRED MEASUREMENT CAPABILITY = 0.450E 02. WORTH AT D.M.C. GROSS WORTH = 0.60, NET WORTH = 0.43
   MINIMUM MEASUREMENT CAPABILITY = 0.180E 03.
   FORM OF WORTH VS MEASUREMENT CAPABILITY FUNCTION = 12, SINUSOID, LOG10(ARGUMENT)
```

* MOST STRINGENT OBSERVATION REQUIREMENT FOR EACH OBSERVATION PARAMETER *

GOAL	KNOWLEDGE REQUIREMENT	OBSERVATION OBJECTIVE	OBSERVABLE PROPERTY	PLANETARY BODY	OBSERVATION TECHNIQUE	OBSERVATION PARAMETER	OBSERVATION REQUIREMENT
1	4	13	32	5	36	1	0.170E 07
1	4	13	32	5	36	2	0.350E 05
1	4	13	32	5	36	6	0.900E 02
1	4	13	32	5	36	7	0.900E 02
1	4	13	32	5	36	8	0.900E 02
1	4	13	32	5	36	9	-0.900E 02
1	4	13	32	5	36	15	0.100E-01
1	4	13	32	5	36	16	0.260E 02
1	4	13	32	5	36	20	0.360E 02
1	4	13	32	5	36	38	0.100E 02
1	4	13	32	5	36	39	0.450E 02

PRECEDING PAGE BLANK NOT FILMED.

4.0 SCIENTIFIC AND ENGINEERING OBJECTIVES

4.1 GOALS

The general goal of planetary exploration—to acquire information concerning the planets, other objects in the solar system, and the interplanetary medium—may be divided into the scientific and the engineering aspects. The scientific goals stem from man's desire for knowledge for its own sake; the engineering goals, from his need to understand natural environments in order to improve the design of spacecraft and operations in space. Developing and exploiting commercial and military technology and enhancing national prestige may be considered as additional engineering goals. Although the commercial and military goals are not closely related to planetary exploration, any dramatic mission accomplishment or scientific discovery will improve the prestige of the United States both at home and abroad.

4.1.1 Scientific Goals

The three generally recognized scientific goals of planetary exploration (References 2 and 4) are the following:

1. To understand the origin and evolution of the universe and the solar system. The concern here is with evidence of the original constitution, formation, and evolution of the planets. Although the inner planets have probably lost most of the light elements they once contained, the low atmospheric temperatures and high escape velocities of the outer planets probably have allowed preservation of the original elemental abundance ratio. Planets on which weathering is not rapid (e.g., Mercury and Mars) will have surfaces of great age that may disclose levels of meteoroid bombardment, solar radiation, and the like, as early as four billion years ago. Comparative studies of the internal structure and mass distribution of various planetary types (Earth, Mars, and Jupiter, for example) will provide insight into such evolutionary processes as core formation.

2. To understand the origin and evolution of life. The discovery of indigenous extraterrestrial life would be of the most profound scientific and philosophical importance. If living organisms exist on the planets, their detection will almost certainly require experiments conducted after actual landings. However, the identification of complex organic molecules in planetary atmospheres

would greatly aid our understanding of the processes leading to the appearance of life on Earth. Our search for such chemicals need not be limited to exploration of Mars and Venus, but may include as well the hydrocarbon-rich atmospheres of the outer planets.

3. To understand the dynamic processes affecting terrestrial environments. This goal concerns internal processes such as tectonic activity, as well as externally driven phenomena such as atmospheric circulation, magnetic disturbances, and the like. By observing these processes at other planets, under a wide range of conditions, the scientist hopes to gain a deeper understanding of their operation at Earth. Some of the related observations (the solar wind, for example) are beyond the scope of this study.

4.1.2 Engineering Goals

In addition to having scientific goals, planetary exploration missions have technology goals related to the performance of spacecraft systems, operational mission control, and increased capability for designing improved space vehicles and experiment systems for future missions.

There are two generally recognized engineering goals of planetary exploration (References 2 and 4), the definitions of which are expanded here to afford greater clarity, as follows:

1. To define the interplanetary and atmosphere environments that affect spacecraft design and mission operations. An understanding of alien environments during an extended mission will assist in selecting operational options such as orbital parameters and atmospheric entry probe release time.

2. To define surface environments that affect spacecraft design and mission operations. In order to determine the feasibility of entry probes and surface landers, the scientist must have knowledge of the composition, temperature, and physical properties of the planets.

System performance is also related to long-term reliability, operational testing and monitoring of spacecraft systems, measurement of the environmental effects upon materials and components, and development of automatic and/or redundant control and repair capability.

To attain these technology goals, one must examine the actual and potential problems encountered in our past manned and unmanned space programs and must extrapolate from these experiences to those that may be

encountered in future deep space missions. Spacecraft system and experiment performance will be affected by the natural environments encountered or required to be measured. In many cases, a remote sensor system may have application to both scientific and engineering goals, but with varying resolution requirements. For example, both disciplines are interested in the atmospheric scale height at a given planet. However, the scientific goals may be satisfied by a height definition of approximately 1 kilometer, whereas the engineering goals may be dependent on a resolution of 50 meters.

4.2 KNOWLEDGE REQUIREMENTS

The knowledge requirements are specific but qualitative questions of a broad nature about planetary and space environments and processes. If all the knowledge requirements are satisfied, the scientific and engineering goals of the planetary exploration program will be attained. Many knowledge requirements are associated with engineering and scientific goals. A set of knowledge requirements is presented in Table 3; some of these are relevant to the total planetary exploration area but are outside the scope of this study because they relate to nonplanetary objects or to phenomena which by their very nature cannot be remotely sensed. Table 4 indicates the goals of each knowledge requirement.

Table 3. Knowledge Requirements

Number	Item
1	What types, amounts, and distributions of indigenous extraterrestrial living organisms, or life-associated chemicals, exist? What evidence of previous life exists?
2	What were the environmental conditions and processes in the evolution of past and present life forms?
3	What are the properties and locations of any environments which may favor the future development of indigenous life or the survival and propagation of terrestrial life?
4	What are the physical and chemical properties of planetary atmospheres versus altitude, on global and local bases? What is the role of trace substances in determining atmospheric properties and vehicle performance?

Table 3. Knowledge Requirements (Cont)

Number	Item
5	What are the circulation regime, energy balance, global and local meteorology, and precipitation processes of planetary atmospheres? How do these factors affect vehicle performance and data transmission?
6	How has the present atmosphere evolved, and how is it likely to evolve in the future? What were the nature and evolution of the primordial atmosphere?
7	What are the physical state, chemical composition and distribution of any solid or liquid surfaces beneath the atmosphere? How did liquid bodies, if any, evolve? What chemicals are present that may affect lander performance?
8	What are the nature, origin, and evolution of the surface topography? What is the history of environments affecting the surface?
9	What is the shape of the nongaseous body of the planet? What are the parameters, cause, and evolution of its present state of rotation? How do the planet's shape and motion affect vehicle guidance?
10	What are the structure, composition, mass distribution, and radial and horizontal differentiation of the interior?
11	What are the previous and present sources of internal heat, if any, and how is energy transferred to the atmosphere?
12	What motions and flow patterns exist in the interior? How are they related to the problems of energy balance and intrinsic magnetism?
*13	What are the sources and energizing mechanisms of trapped charged particles, external magnetic fields, and associated electromagnetic radiation? What processes occur at the interface of the planetary environment and the interplanetary medium?

Table 3. Knowledge Requirements (Cont)

Number	Item
*14	How do particle and field environments in the interplanetary medium depend on distance from the sun and on solar activity? What are the properties of the interstellar medium and how does it interact with the interplanetary medium?
*15	What are the past and present environments and composition of meteoroids and dust in the interplanetary medium and near the planets? How are meteoroids, asteroids, and comets related? What are their origins?
*16	What are the topography, composition, internal structure, and surface environments of planetary satellites? How are the orbits of the natural satellites related to their origins?
17	What are the composition, particle size distribution, structure, and origin of Saturn's rings? How do the rings affect vehicle performance and communications?
*18	How do satellites and dust belts interact with planetary magnetic fields and trapped radiation? In particular, how does Io affect the decametric radiation from Jupiter? Are the rings of Saturn responsible for the apparent weakness of its trapped particle environment?
*19	What are the structure, composition, physical properties, and origin of comets? How is their electromagnetic radiation stimulated? How do they interact with the interplanetary medium?
20	Is the general theory of relativity verified by kinematic and electromagnetic experiments involving solar or planetary gravitational fields?
21	What are the optimum usable visible and RF frequencies with respect to time variations, e.g., diurnal, month, year and solar activity? What are the absorption bands in the planetary atmosphere versus frequency?
22	What are the planetary surface features, bearing strength, local thermal or cryogenic environment, and tectonic activity?

Table 3. Knowledge Requirements (Cont)

Number	Item
23	What natural or induced surface radioactivity exists and how does it affect vehicle performance or surface exploration?
24	What effects to system operations are caused by interplanetary and planetary magnetic and electrostatic fields and their respective transition zones? What effect would planetary airglow have on data transmission?
25	What are the requirements for sterilization of the vehicle, operational systems and respective payloads, as defined by the planetary environments?
26	What are the magnetic susceptibility, electrical permittivity, and optical emissivity of the planetary surface? What surface and atmospheric electrical charges and currents exist? What are the surface/atmosphere boundary conditions?
*Not germane to remote sensor study.	

As an example of the association of goals and knowledge requirements, consider the goal of understanding the origin and evolution of the universe and the solar system. This problem involves the original composition of the material from which the solar system was formed. This material is most likely to be preserved in the atmospheres of the outer planets. In order to evaluate the importance of exospheric escape and accretion processes in altering the atmospheric composition, the density and temperature must be determined as functions of altitude.

4.2.1 Scientific Knowledge Requirements

Biology (Requirements 1 Through 3)

The identification of life on other planets will almost certainly require in situ sensors, inasmuch as such life is probably too primitive and sparse to make likely its unambiguous recognition from flyby or orbiter vehicles. But life-associated chemicals, such as amino acids and chlorophyll, may be identified spectroscopically; if they are discovered, knowledge of their chemical and physical environment is needed since the environment is one favorable to processes believed to be associated with the development of life. If, for

Table 4. Relevant Combinations of Goals and Knowledge Requirements

Knowledge Requirement No.	Knowledge Requirement	Goal 1: Origin of solar system (S)	Goal 2: Origin of life (S)	Goal 3: Environment processes (S)	Goal 4: Environments affecting mission (E)	Goal 5: Environments affecting future spacecraft (E)
1	Existence of life	X	X			
2	Life evolution	X	X			
3	Environments for life	X	X			X
4	Atmospheric chemistry	X	X	X		X
5	Meteorology	X		X		X
6	Atmospheric evolution	X		X		
7	Surface chemistry	X		X		O
8	Surface topography	X		O		X
9	Figure and rotation	X			X	X
10	Interior structure	X				O
11	Interior heat	X		X		
12	Internal motions	X		X		
13	Magnetosphere sources, interfaces			X	X	X
14	Interplanetary particles, fields			O		O
15	Meteoroid, asteroid environments	X				X
16	Satellite properties, origin, etc.	O			X	
17	Saturn's rings	X			X	X
18	Satellite-magnetosphere interactions			X		
19	Comet environments	O		O		
20	Verification of general relativity	O				
21	Propogation of waves			X	X	X
22	Surface geology				X	X
23	Surface radioactivity	O		O	O	O
24	Field effects on system operations			X	X	X
25	Biological contamination					O
26	Electrical properties	O		O	X	X

Legend: (S) - Scientific goal
(E) - Engineering goal
X - Relevant combination in context of study
O - Relevant combination in some respects, but not in this study

example, such substances were found in the atmosphere of Jupiter, credence would be gained by the hypothesis that these and more complex substances arose on Earth in a primitive reducing atmosphere.

Atmospheric Sciences (Requirements 4 Through 6)

The abundances of hydrogen and helium and their ratio are of paramount importance because of their cosmogonic and, possibly, cosmologic, implications. Next in importance are the abundances of carbon and heavier elements—including, at least, potassium and argon; next in line are the isotopic ratios, especially $^{13}C/^{12}C$, $^{2}D/^{1}H$, $^{3}He/^{4}He$, $^{36}A/^{40}A$. All these are potential clues to the origin and evolution of the Galaxy and the solar system. Quantitative determination of trace substances is of particular interest in connection with color and albedo changes, such as in the belts and zones of Jupiter.

Knowledge of depth, scale height, and temperature and density distributions is largely hypothetical in the case of the outer planets, and only rudimentary for Venus. Only for Mars are these quantities reasonably well known; the atmosphere of Mercury is also undefined but surely of a very low density.

Basically, an understanding of how each planetary atmosphere works is desirable. In the case of Earth, the operational mode is different in the troposphere, stratosphere, mesosphere, and thermosphere. Various differences are to be expected for the other planets. The appropriate questions are these: (1) What are the heat sources and sinks for each layer in the atmosphere? (2) How do the heat sources and sinks generate available potential energy for the atmosphere? (3) How is this available potential energy converted into kinetic energy? (4) How is the kinetic energy redistributed and finally dissipated in the atmosphere?

In order to study the energy cycle, one needs to know the temperature, density, wind, and composition as a function of latitude, longitude, height, and time. Variations with latitude and longitude are just as important as variations with height for some aspects of the energy cycle.

Knowledge is needed of the distribution of solar radiation—with wavelength as a function of depth or, alternatively, the distribution of ultraviolet absorbers, the distribution of infrared absorbers—as a function of depth together with temperature and pressure, and the distribution of substances which may contribute to the heat balance through latent heat effects. In addition, the boundary layer heating should be determined; indications are that it may play a greater relative role for the outer planets, with their possible internal heat sources, than for Earth.

The value of studies of atmospheric evolution will depend largely on chemical and geological investigations at the surface, but useful information will be obtained from determination of exospheric escape rates and from comparison of the present states of various atmospheres.

Geophysics (Requirements 7 Through 12)

The study of the solid and liquid planetary surfaces may furnish the answers to many questions concerning the origins and evolution of our solar system. Very few measurements can be made remotely—in part because of the complex nature of condensed materials. However, present knowledge is often so meager in certain areas that even the most elementary data represent great improvements and can impose major constraints upon theories concerning the origin and evolution of the solar system. In addition, a study of other planets and their origins and evolution may provide even a deeper understanding of terrestrial processes. For example, an understanding of planetary volcanism may aid in our knowledge of terrestrial volcanism.

Perhaps the simplest and most fundamental observables are related to the size, shape, mass, and mass distribution of the planets. The sizes (volumes) and masses of the inner planets are known well enough to enable scientists to calculate densities of a precision high enough to deduce whether these planets have metallic cores. From present data (Table 5), it appears that Mercury, Venus, and Earth possess relatively large dense cores, whereas the moon and Mars have, at most, small cores.

Table 5. Masses, Radii, and Densities of the Inner Planets

Planet	Mass (kg)	Radius (km)	Density (gm/cm^3)
Mercury	3.26×10^{23}	2434	5.43
Venus	4.87×10^{24}	6056	5.25
Earth	6.04×10^{24}	6378	5.52
Mars	6.43×10^{23}	3410	3.89

Investigation of surface topography calls for imaging sensors and appears to be feasible only at the inner planets.

The internal heat balance problem is of greatest importance at Jupiter; the net outward heat flow must be determined more accurately to show whether it can be accounted for by gravitational heating during formation of the planet. Information on the internal heat balance and energy regime may be obtained from atmospheric circulation and magnetic field data. The atmospheric circulation approach has been mentioned earlier. The utility of magnetic observations is discussed in Section 5.1.

Particles and Fields (Requirements 13 and 14)

These knowledge requirements are outside the scope of the study inasmuch as they involve <u>in situ</u> observations, but they are included in Tables 3 and 4 for completeness.

Miscellaneous Objects (Requirements 16 Through 19)

These requirements deal with nonplanetary bodies and are outside the scope of the study. An exception is determination of the particle size distribution and composition of Saturn's rings. This information may reveal whether the rings are disrupted satellites or are remnants of the diffuse material from which Saturn was condensed. In the first case, the rings may be relatively transient phenomena, and the absence of rings at other planets would be at least partly explained.

General Physics (Requirement 20)

Verification of the general theory of relativity is not properly a planetary investigation but merely takes advantage of the planets, and so is outside the scope of the study. Experiments for this purpose are suggested in Reference 4.

4.2.2 Technology Knowledge Requirements

Fundamental knowledge of specific technologies is a prerequisite for systematic development of spacecraft and experiment systems for future planetary and deep space missions. The listed knowledge requirements indicate dedication to a maximum use of this information for exploiting and satisfying the engineering goals.

Telecommunications (Requirements 5, 17, 21, and 24)

The optimization of the communication subsystem must consider the transmission frequency, type of modulation, antenna design, RF power conversion, electric and magnetic fields, as well as the data format scheme and means for data storage and retrieval. Frequencies in the centimeter band are of course prime candidates; however, the potential of attaining greater communication capability with reduced power in the millimeter range should be evaluated thoroughly. All the experiments and the operation of the vehicle and associated systems are dependent on the information relayed to ground stations. The optimum design for a reliable communication/data subsystem must consider the degree of attenuation, reflections, occultation, phase shifts, planetary and interplanetary magnetic and electric noise contributors, etc., that can be tolerated and still allow useful data to be recovered.

For a given data transmission system, the rate of data transmitted (in bits per second) is proportional to the received signal plus noise-to-noise ratio. Limits and vehicle configuration (size and weight) impose limits on bit rate and received signal power since transmitted power is limited. New methods and techniques will have to be developed for increasing the data information without imposing severe penalties on weight, volume, and power requirements. The quantity of information to be returned from planetary missions over a period of years imposes another constraint on the design of an adequate communication/data system.

Atmospheric Environment (Requirements 4, 5, 17, and 26)

The design of the initial experiment systems and the attainment of the primary engineering goals will depend on the data about the various planetary atmospheres. Determination of the chemical and isotopic composition, pressure and temperature distributions, heat balance, and circulation (local and global) will be necessary. It is desirable, also, to search for complex organic chemicals and trace elements. Such critical design parameters as entry probes, surface landers, protective devices, communication capability, and spacecraft and experiment hardware will be affected.

The design of an entry heat shield system will depend on knowledge of the scale height, density, and composition of the atmosphere. For example, atmospheres containing a high percentage of CO_2 will intensify the radiative heating of the heat shield; similarly, heating rates are proportional to velocity in a dense medium. When this information is translated into engineering data, considerable weight saving may be achieved. Another area of concern is communications blackout, which may depend on atmospheric composition, electron density, and collision frequency rates. For each phase of the mission, it will be necessary to determine when blackout may occur in terms of density, the frequency utilized, and other variables, and when it will be reestablished.

At a planet with little or no atmosphere (Mercury), for example, the retardation systems for landed vehicles utilize retrorockets; however for landed missions on other planets containing atmospheres, consideration will be given to parachute systems. The effects of atmospheric properties—density (primarily), altitude profiles, and wind shear data—are required before a retardation system concept can be developed.

Surface Environment (Requirements 7, 22, 23, 25, and 26)

In the conceptual design of a landed vehicle and in establishing its feasibility, knowledge of the expected surface environment is the paramount consideration. Such parameters as pressure, temperature, local conditions (thermal or cryogenic), thermal conductivity, magnetic and/or electric fields, load-bearing strength, tectonic activity, etc., will have an effect on the design of the operational and experiment systems. Surface environment investigation is necessarily allocated a lower priority in the early missions when the atmosphere surrounding the planet is dense. Subsequently, additional data will identify various spectral windows, in which surface data can be acquired by remote sensors. For example, design of adequate thermal control and protective systems and their associated weight, volume, and power requirements will be dependent on identification of temperature (as a function of time, season, locale), albedo, topography, and the like. Another major system design is the configuration of the lander pads, a factor directly dependent on the load-bearing strength of the soil, any tectonic activity, and the topography. Most of the initial remote sensor data on surface environment will be obtained at Mars, Mercury, and—to a lesser extent—at Venus.

5.0 OBSERVATION AND MEASUREMENT REQUIREMENTS

5.1 OBSERVATION OBJECTIVES

The knowledge requirements presented in Section 4.2 are stated in terms of basic phenomena and processes, some directly observable and some inferred from observations. As the next step toward quantitative definition of measurement requirements, a set of observation objectives must be formulated which contains descriptions of immediate observation purposes. The following example illustrates the distinction between knowledge and observation requirements: understanding the origin and evolution of planetary atmospheres is a knowledge requirement while determination of the molecular composition of the atmosphere is an observation requirement. One of the observable properties of the atmosphere is its infrared absorption spectrum. The required spectral observations can be defined by specifying the measurements to be performed, such as the range of wavelengths and the solar illumination angle.

Table 6 lists the planetary observation objectives established for this study. A few of these (numbers 20, 23, and 26) are outside the scope of this study, while others (e.g., number 8) will fail to lead to remote measurement requirements. Table 7 indicates by marks (X) the combinations of goal, knowledge requirement, and observation objective relevant to this study. Table 12 presents the values of w_{km}, the worth of the k^{th} observation objective with respect to attainment of the m^{th} combination of goal and knowledge requirement. The scale of the w_{km} is 0 to 1. The values were obtained from consultants' reports (Appendix B) and from assessments by specialists in the various observation disciplines. If no mark appears in Table 7, the combination is judged irrelevant or to have $w_{km} < 0.10$.

To continue the example of the top-down approach begun in Section 4, the requirement for knowledge of atmospheric physical and chemical properties, as related to the goal of understanding planetary evolution, leads to the objective of observing the pressure, density and temperature of the atmosphere as functions of altitude, latitude, and sun angle.

5.1.1 Scientific Observation Objectives

Biology (Objective 8)

With the exception of imaging experiments at Mars, remote observations bearing on extraterrestrial biology are limited to those of atmospheric

Table 6. Observation Objectives

Number	Description
1	Planetary figure, rotation, precession, perturbations of motion
2	Atomic, molecular, isotopic composition of interior substances
3	Internal temperature, pressure, density distributions
4	Internal energy transfer rate and direction distributions
5	Geologic structure and activity, and mineralogic composition of interior and surface
6	Physical properties (mechanical, thermal, electrical) of interior substances
7	Atomic, molecular, isotopic composition of surface materials
8	Motion, structure, replication of organic complexes
9	Surface temperature, heat transfer rate, and direction distributions
10	Topography; evidences of volcanism, impacts, erosion of surface features; tectonic activity
11	Physical properties of surface materials
12	Atomic, molecular, ionic, isotopic composition of atmosphere
13	Atmospheric temperature, pressure, density distributions
14	Circulation patterns and energy transfer rate and direction in atmosphere; wind velocity and direction, dust storm intensity, meteor debris, aerosols, and the like
15	Phase transitions in atmosphere; cloud structure; precipitation forms, composition, and amounts
16	Electric and magnetic fields (interior, surface, atmosphere, space)

Table 6. Observation Objectives (Cont)

Number	Description
17	Ionizing radiation environments (surface, atmosphere, space)
18	Nonthermal electromagnetic emission characteristics and source location
19	Gravity field distribution (surface, atmosphere, space)
20	General relativistic optical and mechanical effects
21	Electromagnetic (radio, optical) reflectivity, absorptivity
22	Occultation (radio, optical) of natural and artificial sources by planet
23	Meteoroid, asteroid, cosmic dust environments
24	Saturn ring gross structure, composition, particle size distribution
25	Vehicle performance (trajectory, atttitude, aerodynamics, subsystems status, and function)
26	Navigation and guidance
27	Data transmission and signal propagation
28	Radiation-scattering properties of cloud tops and atmosphere above clouds

chemical properties. The biological observation objectives, therefore, are discussed implicitly in connection with atmospheric sciences.

Interiors and Surfaces (Objectives 1 to 7, and 9 to 11)

Current belief is that the decay of radioactive nuclides heats the interior of planets. At high temperatures, reducing materials (presumably carbonaceous) in the primordial planetary material reduce oxidized iron to molten metal which sinks to form a core. While it is often assumed that planets all have a composition close to that of carbonaceous chondrites, it appears that Mercury, Venus, and Earth have large cores and too much iron for this

Table 7. Association of Knowledge Requirements and Observation Objectives

	Knowledge Requirements	Observation Objectives																											
		Figure, rotation	Interior composition	Interior temperature	Interior-energy flow	Geologic structure	Interior physical properties	Surface composition	Biological activity	Surface temperature	Topography and tectonics	Surface physical properties	Atmosphere composition	Atmosphere temperature	Atmosphere circulation	Clouds, precipitation	Electric, magnetic fields	Particle radiation	Nonthermal EM emission	Gravity fields	Relativistic effects*	Optical, RF reflectivity	Occultations	Meteoroid environments	Saturn ring properties	Vehicle performance	Guidance and navigation*	Data transmission	Scattering from clouds
No.	Short title	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	26
1	Existence of life								X				X																
2	Life evolution								X				X	X		X													
3	Environments for life									X	X		X	X		X													
4	Atmospheric chemistry									X			X	X	X	X			X			X	X			X			X
5	Meteorology				X					X			X	X	X	X						X							X
6	Atmospheric evolution		X		X	X				X	X		X	X	X				X										
7	Surface chemistry					X	X	X				X			X	X		X				X	X						
8	Surface topography	X				X				X	X				X	X													
9	Figure and rotation	X				X					X									X		X	X						
10	Interior structure	X	X	X		X	X				X								X	X									
11	Interior heat			X	X		X			X				X	X				X			X							
12	Internal motions	X		X	X		X										X		X										
13	Magnetosphere sources, interfaces																X	X	X										
14	Interplanetary particles, fields*																												
15	Meteoroid, asteroid environments	X											X											X					
16	Satellite properties, origin, etc.												X				X												
17	Saturn's rings																					X	X		X				
18	Satellite-magnetosphere interactions																		X										
19	Comet environments																												
20	Verification of general relativity*																												
21	Propagation of waves	X											X	X			X	X	X			X						X	
22	Surface geology					X					X	X																	
23	Surface radioactivity							X										X											
24	Field effects on system operations												X				X		X										
25	Biological contamination*																												
26	Electrical properties						X					X					X		X			X							

* Not applicable to study

hypothesis to be valid. An even more important problem arises in comparing Mercury and Mars. The extent of radioactive heating depends on the size of a planet: the larger the planet, the greater the heating for a given composition. If current beliefs are correct, Mercury, which is smaller than Mars, does not have a core and has a density somewhere between those of Mars and the Moon.

The study of the optical and dynamical oblateness of planets, if measurable, is necessary to deduce the fluidity of the planetary interior and the degree of hydrostatic equilibration. Even Mercury, which presently has a slow axial rotation (59-day period), and possibly a metallic core which indicates fluidity, may present surprises. Its rotation period may have been much shorter in the past and hydrostatic adjustment is not necessarily complete. By analogy, isostatic readjustment on Earth is not complete in areas of mountain building. Further, nonradial distribution of mass, as in the lunar mascons, can be investigated by precise tracking of satellites of planets. Important questions to be answered are: Is the density of Mercury as high as our best present values? If so, Mercury has a core. Why does Mercury, which is smaller than Mars, have such a core? Is the presence of a core a necessary and sufficient condition for fluidity?

Remote measurements of the magnetic fields of planets are possible. These fields, very small for the Moon, Venus, and Mars, are unknown for Mercury and should be measured. Measurements of thermal radiation by infrared (IR) or microwave radiometry to deduce the net thermal budget of planets is important for understanding the contribution of internal heat sources. The measurement of thermal radiation in a traverse across the terminator will also provide an approximate value of thermal conductivity or surface materials. If a long-lived satellite is employed, temporal variations in thermal emission will give an idea of thermal conductivity of planetary surface layers and of possible local internal heat sources. These measurements are especially significant for Mercury, where present theory requires volcanic activity as extensive as on Earth, with many localized heat sources.

The most significant measurements are of the composition of planetary surfaces. Imagery of planetary surfaces, except possibly at long wavelengths, is limited to the inner planets, but the following discussion is presented for the sake of a coherent treatment of surface observations. Imagery gives an idea of the fluid properties of magmas (if they exist), which is a measure of the acidity of the magma. For example, forms and shapes observed in the lunar maria are consistent with the flow of basaltic materials, which has been confirmed. These deductions are indirect and not always fully convincing. More direct measurements are obtained from radiation. The most promising is γ-ray spectrometry, which can measure the amounts of radioactive nuclides of K, U, and Th in planetary surfaces. There is a close correlation between

the concentrations of these radioactive nuclides and the kinds of rocks. This correlation appears valid for the moon where early Soviet γ-ray measurements with the Luna 10 orbiting vehicle indicated that the maria were basaltic. Even these early, crude measurements provided a significant conclusion. Improvements in techniques will be tested in lunar orbit and should be available for studies of other planets. In addition to γ-ray spectra, x-ray and α-particle spectra should prove significant. Breakthroughs in IR, visible, and ultraviolet (UV) reflectance spectra, as well as in measurements of neutron albedo or neutron scattering, will be necessary for them to be useful. Most important are measurements of the average composition of the surfaces of Mercury and Mars. Fundamental questions must be answered. Is Mars' surface like the moon, is it more acidic like the Earth, or is it closer to chondritic composition? Is the surface of Mercury acidic? If not, then volcanism is not as extensive as on Earth, which raises the question: how was the core formed? Present theories of the origin and evolution of planets are often supportable only because of their age and the lack of competing hypotheses. Even crude data are needed to test them.

Atmospheres (Objectives 12 to 15, 21, and 28)

Atmospheric properties of interest can be divided into those related to the global and nearly stationary state of the planet (chemical and isotopic composition, global averages of pressure and temperature, radiation absorption and scattering, and the like), and those related to atmospheric kinematics and dynamics such as circulation motions, precipitation, and local variations in pressure and temperature.

The spectral energy distribution of thermal radiation from the planets in the radio, microwave, and infrared ranges may give information on temperature gradients below the visible cloud tops and help detect internal heat sources. Such heat sources are believed to account for the excessive radiation temperatures of Jupiter and possibly Saturn over that which balances the solar flux. Detailed thermal mapping will also help understand radiation exchanges in the atmosphere below the cloud tops.

The requirements and interpretation of atmospheric spectral measurements are discussed at greater length in Section 5.2 and Appendix A.

Observations of stellar occultations can give information on exospheric temperatures, escape rates, and (through the scale height variations) the H/He ratio. Observations of radio occultations could give information on molecular and electronic densities over a larger pressure range ($\lesssim$1 atm). Airglow observations, i.e., of night-side emissions such as the 584-A He resonance line, could also contribute pressure and density data and disclose precipitation of trapped electrons into the upper atmosphere.

Detailed and integral scattering properties of the outer planets are not well known because the phase angle never exceeds a few degrees; thus the phase functions and integrals cannot be observed and computed. It follows that the spherical albedos are unknown, except in unverified model atmosphere calculations. This fact, and the incompleteness of the spectral energy curve, combine to leave the radiometric albedo almost indeterminate within wide limits (at least 50 percent uncertainty). In addition to multicolor phase curves over a large range of phase angles, detailed observations of the monochromatic limb-darkening laws along the equator and the meridian are needed. The abundances of major constituents in the Jovian atmosphere (H_2, He, NH_3, and CH_4) have begun to approach self-consistent and reproducible numbers (Reference 8). However, the concentration of major constituents of the other outer planets remains much less certain. To make better estimates of the atmospheric structure below the clouds, the composition of the upper atmospheres must be measured more precisely. In addition to H_2, He, NH_3, and CH_4, important components of these atmospheres may include HD, D_2, and other noble gases, as well as H_2O, H_2S, and the like. Several experiments projected for spacecraft show promise for such measurements, including absorption and emission spectra of radiation in the UV, visible, IR, and microwave regimes. Because of their cosmological significance, the ratios of H/D and H/He should be determined as accurately as possible.

Along with spectroscopic measurements for major constituents, attempts should be made to find trace components such as purines and pyrimidenes (for their relevance to biological materials), ethylene (believed to be in the Saturnian atmosphere), and ammonium hydrates or hydrated sulfides (in clouds). Determination of the average global composition will be of great significance. However, obtaining distributions of major constituents with latitude and longitude and in regions of different color or albedo would provide more information about planetary structure. Obtaining such spectral data would require much greater sophistication than the global average measurements alone.

In addition to electrically neutral species, information about concentration distributions of ions such as H^+ and He^+ would be very useful in constructing more detailed models of the photochemistry of the ionospheres (Reference 9).

Temperature, Density, and Pressure Distributions. To develop better models of the atmospheres of outer planets, it is vital to obtain vertical distributions of density, temperature, and pressure as far down into the atmosphere as possible. Three possible experiments can be used: (1) a stellar or radio occultation investigation, (2) investigation of the absorption line shapes of gases like NH_3 and CH_4 by high resolution infrared or microwave spectroscopy, and (3) observation of filtered radiation during limb darkening. The

apparent temperature of the cloud level can be derived, of course, from radiometric measurements at several frequencies (i.e., Reference 10). It may be possible to map the horizontal thermal structure of the clouds by radiometry, and it may be possible to penetrate deep into the atmosphere by radiometry near 10 millimeters.

Closely associated with the study of horizontal and vertical distributions of temperature and density is the analysis of thermal emission. Since models based on simple reflection and Rayleigh scattering from a homogeneous atmosphere do not agree with observations, inhomogeneities from scattering sources such as cloud layers must be accounted for (Reference 8).

It appears that radiation from Saturn and Jupiter can be explained only by considering an unknown internal source of heat. Furthermore, Goody (Reference 8) has given arguments suggesting that Jupiter cannot be in radiative equilibrium. Motion in the atmosphere plays a modifying role, and may indeed control the thermal structure near the cloud tops.

Many questions about the thermal structure of the outer planets' atmospheres can be derived from straightforward astronomical observation (Reference 10). For example, measurement of the bolometric thermal flux will better fix the effective temperature of the planets. The observations must be made in this case over the entire thermal spectrum, say, from 5 to 100 microns beyond the Earth's atmosphere.

Other fundamental quantities to be determined are the Bond albedo and the phase function (Appendix B). The Bond albedo will provide a direct indication of the solar input to the planet's radiative flux.

Combined with observation of the bolometric thermal flux, the Bond albedo will yield a direct estimate of any internal heat source. Determination of the phase function at many wavelengths will give data on the scattering media responsible for diffuse reflection in the atmospheres. It also will yield data to calculate the phase integral, an unknown part of the Bond albedo. In addition to the observations over a broad wavelength range and measurements of thermal flux at several wavelengths, such results can be used to distinguish between various models. By choosing intervals to contain different opacities (Reference 10), the ratio of flux from the two regions identifies models which best fit the observations. For example, the radiative flux from Jupiter in the 17- to 33-micron region would characterize the upper layers, while the flux measured in the 33- to 100-micron region would identify the lower layers. In combination, they would present a strong observational constraint on the speculated atmosphere structure.

Observations of limb darkening also will give information on various layers of the atmosphere. For example, some knowledge of sources of extinction at different levels should be attained along with some checks on opacity sources and the importance of Mie scattering. By making limb-darkening observations at wavelength intervals with different average opacities, the atmosphere structure can be studied to great depths. Comparison of the equatorial and meridional limb-darkening curves should provide further knowledge about the extent of latitudinal heat flow and the relative magnitudes of internal and solar sources of heat. Direct radiometric scanning of the disk at various wavelengths should yield meridional and longitudinal gradients in temperature at different depths in the atmosphere. Such information will reveal much about the atmospheric dynamics including the nature of correction and turbulence in the atmospheres.

Probing the atmospheres of the outer planets with 10-cm microwave radiometers may reveal apparent heterogeneities in the deep layers of the atmosphere. From combined radiometric and radar measurements, the nature and depth of a solid or liquid interface in the planet may be identifiable. If the interface is liquid, it may be possible to make a thermal map of the planet's surface by microwave radiometry. Unfortunately, the possibility of penetrating deep into the Jovian atmosphere, even with microwave devices, appears remote because of the planet's nonthermal radio noise. However, more success in such experiments may be achieved on missions to the other planets.

Knowledge of the motion field is required on all scales at which energy conversion may occur. When air flows down the pressure gradient, the kinetic energy of the air increases. An alternative formulation involves warm air rising and cold air sinking. In general, it is very difficult to measure the vertical motions, even in the Earth's atmosphere, and deductions from the horizontal motions seem to offer the best possiblity. The strongest clue to the motion fields is in the presence of a banded cloud structure on Jupiter, Saturn, and Uranus; the resemblance is clearly to terrestrial Hadley cells rather than to the perturbed wave circulations of terrestrial middle latitudes.

From extensive research on the large-scale dynamics of the Earth's atmosphere, basic ideas have developed which can be applied to the behavior of other planetary atmospheres. For rapidly rotating planets that are thermally stratified, theory suggests that the wind structure should be bounded into zonal flow patterns. If instabilities develop by barotropic or baroclinic disturbance, one can expect planetary waves to form with possible cyclone formation. The observation of cloud patterns on Jupiter generally bear out the theoretical predictions (References 11, 12, and 13). While banded structure has also been observed on Saturn, it is uncertain on Neptune and Uranus because of their great distances from Earth.

There are major potential differences in the general circulation of the outer planets' atmospheres compared with Earth. The question of internal heating on Jupiter and Saturn is important from the standpoint of the hydrostatic stability of the atmospheres. If there are no liquid or solid phases (at least strong density discontinuities) on these planets, strong thermal or orographic disturbances may not be possible, giving rise to more prevalent banded structure than on Earth despite the atmospheres possibly being in an unstable Rossby wave regime. Uranus may be unique in its circulation because it rotates (during the 1975 to 1995 time period) with a pole toward the Sun rather than with equator to Sun. The solar heating, through much weaker at Uranus' distance, may drive a peculiar atmospheric motion on this planet.

Particles and Fields (Objectives 16 to 18)

Observations of charged particles and electric and magnetic fields are generally outside the scope of this study. An exception is inference of interior differentiation and motions from the external magnetic field; this is discussed under interior observations.

5.1.2 Technology Observation Objectives

The technology observation objectives are closely interrelated with the science observation objectives, and in many cases are indistinguishable. These objectives should include the expected range of the observable environments, the vehicle, and interfering phenomena such as solar noise emission and planetary and/or atmospheric data as discussed under science observation objectives. The objectives should define the times and places at which the observable should be carried out (that is, the times and planetary regions in which the measurable phenomena exist) rather than where the sensor is located. It is also necessary to specify the spacecraft trajectory requirements, and understand how related measurements on a given mission reinforce the observation in question. If the observation conditions are adequately defined, appropriate sensor systems and supporting subsystems can be selected to carry out the experiments.

Using a top-down approach, each objective leads to a series of investigations and each in turn leads to a series of sensor systems. A given instrument (sensor) may relate to several different investigations. Sometimes a given investigation may relate to more than one objective. For example, establishing the atmospheric circulation is a definable engineering objective. Two observables, cloud motion and chemical composition, can be combined to formulate a descriptive model of this phenomenon. Instrumentation (sensors) that contribute to knowledge of cloud motion are camera imaging systems (IR and visible), bistatic radar, and telescopes. Sensors that define atmospheric circulation are spectrometers (IR and visible), RF occultation, and Lidar.

The knowledge requirements that must be fulfilled by engineering experiments are largely established by the data requirements and the conduct of the flyby and orbital missions. The design of guidance and navigation systems for such missions requires knowledge of such planetary characteristics as the figure (that is, the diameter as a function of direction from the center) and the gravitational field distribution. The present uncertainty regarding radiative environments, particularly around Jupiter, implies considerable uncertainty in radiation shielding and material protection devices. To reduce the weight penalty for these protection systems within allowed safety margins, the corresponding environments must be an observation objective.

Atmospheric Engineering Models (Objectives 12 to 15, 25, and 27)

The engineering objectives in the design and development of an aerospace vehicle are, in order of usual importance:

1. A successful/reliable vehicle
2. An efficient/economical vehicle.

These objectives must consider the atmosphere in which the vehicle will operate. Success is ensured against failures due to atmospheric conditions by designing the vehicle for short-term operation in extreme atmospheric conditions, and efficiency by designing for long-term operation in nominal or mean atmospheric conditions. Nominal and extreme (or seldom-exceeded) engineering model atmospheres are required for both objectives.

The vehicle operations that must be considered include flyby, orbit, entry/descent, landing/stay, and launch/boost. Of these, flyby and orbit operations are usually confined to experiment objectives and are little affected by planet atmosphere unless the experiment itself depends on the atmosphere. Atmospheric conditions during entry, landing, stay, and launch/boost operations, on the other hand, directly affect the space vehicle design.

Model Categories. Engineering model atmospheres ideally show hydrodynamically consistent profiles of temperature, pressure, density, and their engineering derivatives. The models may be divided into three categories according to their complexity and confidence level.

1. Category 1. A first approximation may be achieved by the isothermal/exponential model atmosphere which requires the following data: estimate of mean isothermal temperature, estimate of the mean molecular weight or the average scale height, and pressure or mass density at any known altitude.

Thus, an isolated or single value for molecular weight/scale height and pressure, together with one or more theoretical or experimental temperature values, may be utilized to construct an exponential, first-approximation model atmosphere.

2. Category 2. Improved model atmospheres, either exponential or hydrostatic equilibrium models, which demonstrate the probable range of atmospheric properties may be constructed if data are collected from different geographical and/or seasonal locations.

3. Category 3. The ultimate engineering model atmospheres may be constructed in the form of hydrodynamically consistent models for geographical locations, each having different season versions, and upper atmosphere portions projected for future time periods via a prediction of solar activity (Reference 14). Extensive observation over long time periods, altitude ranges, and geographical locations are required.

State of the Art. Earth model atmospheres are the only ones which currently apply to Category 3. Category 2 model atmospheres have been proposed for Mercury, Venus, and Mars. For the outer planets, Category 1 model atmospheres are nonexistent except for preliminary Category 2 models for Jupiter (Reference 15) and these apply above the cloud layers only.

Experimental Data for Model Atmosphere Construction. Ideally, the engineering model atmosphere would be constructed from the following observed data:

1. Temperature profile
2. Molecular weight profile
3. Pressure (or density) at a given altitude, preferably the surface.

Such data are most easily collected by an entry probe descending to the surface. However, any remote sensor data, even point data, about the composition and abundances, temperature, pressure, scale height, or density would be useful in the absence of profile data. Such data, for varying seasons, for day and night, and for geographical locations would be of even greater value. For engineering model atmosphere construction, it is most important to acquire data on the constituents believed to be present in major proportions since minor constituents contribute little to the molecular weight, adiabatic lapse rate, densities, and the like. Data regarding H_2, He, and CH_4 are required for the outer planets in particular.

Wind Data. Another atmospheric parameter of engineering design importance is wind speed. For both descent/boost and for occupation stations, the wind speed, in profile and at the surface, is an important design factor from the standpoints of reliability and mission success.

Wind speed data may be measured or may be theoretical in nature. Because the descending probe is undoubtedly the most important wind profile measuring system, the collection of such data from remote sensors is not suggested. On the other hand, the wind speed at a visible surface may be deduced from remotely sensed cloud movements. Such information, when combined with other data, may lead to general circulation theories from which wind speed profiles may be deduced.

Condensates/Particulates. Although not a part of the model atmosphere, knowledge of the particulates (such as dust) and condensates (clouds, precipitation types, amounts, and intensities) would be useful in such engineering applications as structural damage potential in high-speed flight through dust and/or preciptation, and the effects of dust and/or precipitation on electronic systems of landers and long-life occupation systems. Knowledge of these atmospheric properties is less important than knowledge of the model atmosphere parameters.

Ionospheric Structure. Because the electron profile of the upper atmosphere may influence communications between landers, orbiters, and Earth, the collection of electron density data from the ionosphere of the outer planets is warranted.

Surfaces (Objectives 9 to 11, 19)

For definition of surface environments, data on the following parameters are required:

1. Surface light and reflectivity
2. Surface temperature and thermal conductivity
3. Surface load bearing strength
4. Surface features (roughness)
5. Surface electromagnetic properties
6. Surface composition
7. Meteoroid flux, mass, and velocity

8. Figure of planet
9. Tectonic activity
10. Particulate radiations

The resultant data will define the surface effects on the vehicles and measurement subsystem as follows (Objective 25):

1. Thermal control
2. Surface mobility capabilities
3. Surface navigation and communication capabilities
4. Vehicle/surface compatibility
5. Particulate radiation effects
6. Meteoroid mass and penetration
7. Descent and landing capability
8. Surface launch capabilities
9. Surface optical experiments

Interplanetary Medium (Objectives 16 to 22)

For definition of interplanetary environments, data on the following parameters are required:

1. Meteoroids and cosmic dust
2. Solar radiation
3. Magnetic fields
4. Planetary radio emissions

The resultant data will define the interplanetary medium effects on the vehicle and measurement subsystems on an extended mission as follows:

1. Communications (optimum frequencies)

2. Degradation of materials

3. Electronic systems and operations

4. Meteoroid puncture

5. Stabilization and control

6. Spacecraft space charges

There is a recognized third group of measurements other than the scientific and technology types previously discussed. These are called housekeeping measurements (operational and flight qualification), which are in situ measurements located throughout the vehicle and sensor subsystems. This category is outside the scope of this study, but will furnish significant data to satisfy observation objectives. For example, triaxial accelerometers, mounted in the vehicle, will identify permutations of the vehicle during an orbit. These data can be used to compute the figure of the planet or determine whether there are any localized mass concentrations.

Operational measurements are defined as those which remain relatively stable for similar types of mission, and are utilized for in-flight management of the vehicle, mission evaluation, and measurement system performance and inflight checkout of the spacecraft. Flight qualification measurements are defined as those which will vary from flight to flight and define the development state of the vehicle and measurement subsystems. These measurements, along with the engineering and scientific measurements, will provide all the environmental data necessary for a planetary flyby or orbital mission.

Preflight sensor instrumentation development requirements will be examined in Phase 2 of this study. Support equipment development is beyond the scope of the study, but the support requirements will reveal inadequacies of support technology.

5.1.3 Supporting Research

Planetary astronomy from Earth orbit and from surface observatories, as well as laboratory experiments and theoretical calculations, are indispensable supplements of observations at the planets and in interplanetary space. Although these programs are not proper parts of an analysis of remote sensor requirements, they merit attention because they establish minimum space observation requirements (a planetary mission must exceed

Earth-based observation capabilities) and also help scientists understand sensor data. Examples of such supporting research requirements are:

1. Laboratory measurement of collision-induced far infrared spectra of CO_2, CH_4, and NH_3, and mixtures of polar and nonpolar gases found in planetary atmospheres (Reference 22).

2. Calculation of line shapes related to requirement 1 above.

3. Calculation and measurement of the equation of state of hydrogen at pressures up to 3×10^7 atmospheres, which may exist at the center of Jupiter.

4. Synoptic measurements from Earth orbit of infrared and ultraviolet spectra of planetary atmospheres.

5. Development of Earth-based transmitters capable of illuminating outer planets for bistatic radar experiments using receivers on planetary orbiter spacecraft (Reference 4).

5.2 OBSERVABLE PROPERTIES

The properties that can be remotely sensed in principle to accomplish the observation objectives just defined are now considered. At this point the distinction between scientific and engineering data is abandoned. However, Appendix C presents any quantitative differences in the desired observations according to their motivating goals.

The observables considered in this study are listed in Table 8. Many of these are outside the scope of the study, but are included to provide a list suitable for all classes of planetary observation. Table 9 indicates by a mark (x) the relevant associations of observable properties and observation objectives. The worth values w_j of each observable (i.e., of observing the property with attainment of the desired values of all observation parameters) are given in Table C-6. The scale of w_j is 0 to 1, and values of $w_j < 0.1$ are considered to represent irrelevant observations.

In the example of the top-down approach, one of several means of determining atmospheric density versus altitude is to measure the retardation time (phase shift) and attenuation of an electromagnetic signal passing through the atmosphere. If this measurement is made essentially simultaneously at two frequencies, the densities of ions and neutral atoms or molecules can be determined separately.

Discussions of specific observables and observation requirements follow. More detailed treatments of most requirements are given in the

Table 8. Observable Properties

No. (j)	Description
1	Optical images of surface and/or atmosphere
2	Radar images of surface and/or atmosphere
3	Satellite orbital parameters*
4	Chemical/nuclear assay (direct)*
5	Spacecraft trajectory parameters*
6	Active seismic detection*
7	Passive seismic detection*
8	Temperature vs. depth below surface
9	Magnetic field near surface*
10	Magnetic field above atmosphere
11	Mineralographic, petrographic, crystallographic assay (direct)*
12	Gamma ray flux and spectrum
13	Charged particle flux, spectrum, angular distribution
14	Electric field, currents, conductivity at and below surface*
15	Microwave radiation flux, emissivity, absorptivity
16	Microwave spectrum
17	Infrared radiation flux, emissivity, absorptivity
18	Infrared spectrum
19	Visible/ultraviolet radiation flux, emissivity, absorptivity
20	Visible/ultraviolet spectrum
21	Radio flux and spectrum
22	Biological assay and activity*
23	Surface temperature (direct)*
24	Laser beam reflectivity/absorptivity of atmosphere
25	Atmospheric temperature (direct)*
26	Atmospheric pressure (direct)*
27	Radio reflectivity/transmissivity of atmosphere
28	Entry probe trajectory parameters*

*Outside scope of study (in situ observation or nonplanetary observation)

Table 8. Observable Properties (Cont)

No. (j)	Description
29	Electric field and currents in atmosphere*
30	Surface mechanical properties (direct)*
31	Gravitometric data
32	Electromagnetic signal time and ray deflection
33	Wind velocity and direction (direct)*
34	Dust storm intensity and movement (direct)*
35	Radio-frequency permittivity, resistivity, susceptibility
36	Optical permittivity, resistivity, susceptibility
37	Acceleration and deceleration of vehicle*
38	Distance, altitude of spacecraft from topographic features, etc.
39	Electromagnetic phase shift
40	Polarization (amount, type, rotation, etc.)
41	Stellar occultation (photometric)
42	X-ray absorption and emission
43	X-ray spectrum induced by solar electrons
44	Fast/slow albedo neutron flux ratio

*Outside scope of study (in situ observation or nonplanetary observation)

consultants' reports (Appendix B), and quantitative requirements information is presented in Appendix C.

5.2.1 Imagery (Observables 1, 2)*

Optical systems of different apertures and focal lengths, associated with Vidicon-type image sensors, are available to provide direct imagery on a much greater scale and resolution than provided by present ground-based telescopes or envisaged for near-Earth orbital observatories of the next 20 years. For example, practical resolution of one second of arc is seldom exceeded on Earth-bound telescopic photographs of the outer planets which,

*Saturn, Uranus, and Neptune only.

Table 9. Association of Observable Properties With Observation Objectives

		Observable Property																																											
		Optical images	Radar images	Satellite orbital parameters	Chemical, nuclear assay	Spacecraft trajectory parameters	Active seismic detection	Passive seismic detection	Temperature below surface	Magnetic field near surface	Magnetic field above atmosphere	Mineralographic assay	Gamma ray spectrum	Charged particle spectrum	Surface electric field	Microwave flux	Microwave spectrum	Infrared flux	Infrared spectrum	Visible/ultraviolet flux	Visible/ultraviolet spectrum	Radio flux and spectrum	Biological activity	Surface temperature (direct)	Laser beam reflectivity	Atmospheric temperature (direct)	Atmospheric pressure (direct)	Radio reflectivity	Entry trajectory parameters	Atmospheric electricity	Surface mechanical properties	Gravitometric data	Electromagnetic signal time	Wind velocity (direct)	Dust storms (direct)	Radio frequency permittivity	Optical permittivity	Acceleration of vehicle	Altitude of spacecraft	Electromagnetic phase shift	Polarization	Stellar occultation	X-ray flux	X-ray spectrum	Albedo neutron flux
	Observation Objective	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
No.	Short Title	I	I	N	N	N	N	N	N	N	N	N	N	N	N	I, N	N	I, N	N	I, N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	I, N	N	N	I	N	N	N
1	Figure, rotation	X	O															X							X			X																	
2	Interior composition										O			O																															
3	Interior temperature										O			O																															
4	Interior energy flow										O			O		O		X										X																	
5	Geologic structure																																X												
6	Interior physical properties										X			X				X																										X	
7	Surface composition		O										X				O		O	O	O																								
8	Biological activity																																												
9	Surface temperature															X		X										X																	
10	Topography and tectonics		X																													X													
11	Surface physical properties		O													X																				O	O				X				
12	Atmosphere composition																X	X	X	X	X				O			X					X							O					
13	Atmosphere temperature		O													X	X	X	X	X	O	X			O			O					X						O						
14	Atmosphere circulation	X														X		X							X			X					X												
15	Clouds, precipitation	X																							O			X					X								O				
16	Electric, magnetic fields									X	X			*	X																														
17	Particle radiation										*			X																										X					X
18	Nonthermal EM emission										*			*							X	X																		X					
19	Gravity fields																																												
20	Relativistic effects																																												
21	Optical, RF reflectivity															X		O	O	X					O			O					X			O	O			X					
22	Occultations															X																	X							X		X			
23	Meteoroid environments																			X																									
24	Saturn ring properties	X														O			O	O	O	X																				X			
25	Vehicle performance																																												
26	Guidance and navigation																																												
27	Data transmission																																												
28	Scattering from clouds	O														O		X	X	X																					X				

Legend: X Applicable association
O Inappropriate to remote sensing
* Not applicable to study
I Imaging
N Non-imaging

because of the low illumination levels, require long exposures. One second of arc corresponds to the follwoing linear resolutions at mean opposition:

Saturn: 6,000 km Uranus: 12,400 km Neptune: 20,000 km

From direct images, and provided uncalibrated distortions of the electronic readout system do not exceed the resolution limit, diameters and optical ellipticities of the three outer planets could be derived to a degree of accuracy far greater than present ground-based data. This degree of accuracy is 0.1 to 0.2 second of arc on the mean opposition apparent diameter, or about 1 percent for Saturn and perhaps 5 percent for Uranus and Neptune. (The diameter of Neptune is now known more precisely from a recent stellar occultation.) Direct images in several colors will be needed to decide whether the edge of the planet is defined by a definite cloud surface or by a critical optical depth in a molecular or particle atmosphere.

Direct images of large enough scale, obtained over periods of time greater than one rotation period (10 to 16 hours), may provide enough detailed information on motions of discrete cloud formations to establish much more precisely the rotation periods of Uranus and Neptune, and differential rotation as a function of latitude on Saturn (and possibly on the outermost planets).

The conversion of available potential energy to kinetic energy involves air motions; of primary importance are motions in the lower atmosphere. Because density decreases with altitude, the kinetic energy density is low in the upper atmosphere and energy transfer from the lower to the upper atmosphere is more important than the reverse process. A detailed knowledge of motions in the lower atmosphere is therefore required. The only feasible remote technique at present is to use the clouds as tracers of the motion field. Sequential cloud photography of the same region, as from a synchronous orbiter, is required.

The resulting mean motions (averaged over many rotations) would be used to construct the mean circulation pattern and the daily values together with temperature values—required at the same place, time, and resolution—used to compute heat transports.

Special imaging observations of Saturn's rings are described in Appendix B.

5.2.2 <u>Spectroscopy</u> (Observables 12, 16, 18, 20, 21, 42, 43)

The following projects seem to deserve first consideration for spectroscopic observations from flybys: ultraviolet scanning spectrometry at medium resolution, about 1 cm^{-1} (10^3 to 10^4), of the spectral range 0.1 to 0.3 micron, to extend the absorption-reflection spectrum of the disk and, at close range, to search for characteristic fluorescence of upper atmospheres on the dark side; special observation of the resonance lines of helium, (584A), hydrogen (1216A), and other light elements; a search for resonance lines of lowest order of ionized molecules, such as N_2^+ (3114A). Since many other molecules and radicals might be optically active, a complete exploratory program rather than a selective search at a few wavelengths appears advisable.

X-ray and γ-ray spectroscopy to identify surface materials is feasible only at Mercury, whose thin atmosphere should transmit most of this radiation. The observation requirements are similar to those planned for lunar missions (Reference 16). Radio spectrometry is related to magnetospheric phenomena and is outside the scope of the study.

Spectroscopic studies of planetary atmospheres in the visible and infrared region of the spectrum are primarily studies of the intensity, polarization, and strength and shape of absorption spectral bands of the reflected solar energy, and the infrared radiations emitted by the atmosphere. They pertain, mostly to the upper atmosphere in the region near the top of any reflecting cloud layer that may be present. From the infrared absorption band spectra of the planet, the constituents of the atmosphere can be identified; and from studies of relative intensity distribution of the various absorption spectral bands, the temperature of the atmosphere where these bands are formed may be estimated. Studies of the polarization of the reflected solar energy can potentially yield information regarding the properties of the particulate matter of the clouds. Studies of the infrared thermal emission from the atmosphere give the temperature of the atmosphere at a depth where the infrared opacity is near unity. Therefore, the main types of information deducible from these measurements are the constituents and their relative abundances in the atmosphere, and the temperature and density of the atmosphere.

It is generally quite difficult, however, to extract these physical properties of a planetary atmosphere from the observed spectra, and the results obtainable depend almost entirely upon the particular theory of line formation adopted to interpret the spectra. In particular, if the atmosphere is optically opaque and the lines are formed at large optical depths through multiple scattering, the problem can be enormously complicated and can often lead to unreliable results with large uncertainties. Relationships between atmospheric spectra and physical properties are developed in Appendix A.

5.2.3 Radiometry and Photometry (Observables 15, 17, 19)

Infrared Radiometry

Thermal detectors associated with broad-band filters and/or low-resolution spectrometers should be used to derive the energy distribution of the thermal emission of the planets in the 5- to 25-micron range. With radiative equilibrium temperatures of the outer planets in the 50 K to 150 K interval, the expected maximums of the spectral energy curves are in the 20- to 60-micron range; however, departures from a simple black-body curve at a single effective temperature may be observed if, at least in the case of Jupiter and Saturn, internal heat sources play a significant role in the heat balance of the planet. Detailed observations of the distribution of thermal emission over the disk of Saturn (including the dark side) with a resolution of at least 10 x 10 elements (20 x 20 elements may be needed to resolve the belt structure clearly), as well as total radiation spectra of Uranus and Neptune, are required to supplement the temperature indications from spectroscopic and microwave radiometric studies.

Attempts to detect thermal emission from the dark side of Uranus and Neptune would also be of value to check on possible internal heat sources. If thermal maps of these planets can be obtained at one or two wavelengths in the expected range of maximum emission (40 to 60 microns), a resolution of 10 x 10 elements should be sufficient to attempt correlation with possible belt structures.

Infrared radiometry of Mercury is primarily an imaging observation to obtain thermal maps of the surface. At Venus, experiments similar to those at the outer planets can be performed to determine lower atmospheric temperatures, except that the cloud top temperature is near 250 K. It is expected that, by the 1975 to 1985 time period, remote observations of the Martian atmosphere and surface will have been superseded by entry and lander experiments.

Microwave Radiometry

The millimeter and centimeter waves cover a spectral region of great importance for the thermal balance of cold planets and include some discrete absorption lines of major significance. Microwave observations from flybys, if possible with some angular resolution (10 x 10 on Jupiter and Saturn, 5 x 5 on Uranus and Neptune), deserve a high priority. Continuum emission measurements near wavelengths 0.3, 1.3, and 10 cm should be sufficient to define the thermal spectrum and effective temperature. Of special interest are observations at 1.25 and 1.35 cm, corresponding to the absorption lines of NH_3 and H_2O; positive detection and study of the center-to-limb and center-to-pole variations should greatly assist development of theories of the cloud and atmospheric structures. Such observation is likely to be simpler for Saturn if there is an internal heat source providing a stronger background emission than in the case of pure solar heating. Again, if internal heat is present, microwave emission might be detectable on the dark side of the planet. Study of the day-night cycle of emission at several wavelengths will help separate the contributions of the internal and external heat sources.

Photometry

Photometry in the visible spectrum should be one of the most important tools in an investigation of the outer planets by remote sensors because of the phase angle and resolution limitations of ground-based observations. It will be necessary to determine the normalized (relative) integral intensity of the planet as a function of phase angle from 0 degrees (opposition, full phase) to as close to 180 degrees (Sun occultation) as possible and over a wavelength range as large as possible, at least from 0.2 to 5 microns.

It will be especially important to determine directly the phase function F (i) and phase integral q, which are still unknown because of phase angle limitations; according to theoretical calculations, q may range from 1.25 for Rayleigh scattering to 1.45 for isotropic scattering to 1.77 for some models of anisotropic scattering. This uncertainty is reflected in the value of the spherical albedo A = pq, where p, the geometric albedo, is the only factor known from ground-based observations.

5.2.4 Polarimetry (Observable 40)

Light reflected by the planets is partially polarized in a manner characteristic of the nature and structure of the scattering particles. The degree of polarization is generally small, often less than 10 percent, but it could be large under some circumstances; for instance, a Rayleigh *scattering atmosphere observed at right angles to the direction of incidence* may have close to 100-percent polarization. Because of the severe restriction of phase angles observable from Earth, and the faintness of the light of the two outer planets, this technique has not yet delivered its potential. The situation will be quite different from spacecraft if a large range of phase angles is observable at distances small enough to give good resolution of the disk.

Even at large ranges, a fair degree of polarization of the total light of Uranus and Neptune, possibly 30 to 50 percent, might be observed, if, as has been suspected, Rayleigh scattering plays a major role in explaining the

blue-green colors of these planets. More important will be studies of the detailed distribution of polarization over the disks and particularly center-to-limb darkening curves in the two main directions of the electric vector (along the radius and perpendicular to it). This information at several wavelengths, selected by broad-band filters, is essential for a detailed verification of theories of atmospheric scattering and for differentiation between molecular and particle scattering as the main contributor to the diffuse reflection of sunlight by the outer planets. The relative contributions are expected to vary with latitude, particularly in the polar regions, where preliminary information on Jupiter and possibly Saturn suggests that pure molecular scattering may be dominant.

5.2.5 Coherent Light Observations (Observable 24)

Optical radiation is scattered and absorbed in a planetary atmosphere by the gaseous molecules, natural aerosols, and particulate matter present. As a result, a light beam decreases in intensity as it passes through an atmosphere while some light is observed to the side and rear of the original beam. Some of this scattered light may be partially or completely polarized, even though the original beam was unpolarized. A weak component is observed which is also at a different frequency (Raman scattering) but is of greatly reduced intensity compared with the intensity of the scattered light of the original frequency.

In the Earth's atmosphere, the majority of the scattering and absorption occurs as a result of aerosols and particulate matter such as clouds, haze, and smoke. This part of the scattering is adequately described by the Mie theory, which treats it as an electromagnetic-wave boundary problem on spheres.

It may be possible to aim a laser beam, in the visible or infrared, at the planetary atmosphere and, at another spacecraft, to observe the Mie-scattered radiation from suspended particles such as crystals of solid CO_2, NH_3, and CH_4.

5.2.6 Occultations (Observables 27, 32, 39, 40, 41)

Two general classes of occultation experiments can provide, with minimal spacecraft sensor and experiment support requirements, valuable information on the density and composition of atmospheric neutral (atoms, molecules) and ionized (electrons, ionized atoms and molecules, and free radicals) particles as a function of altitude. Sources of electromagnetic radiation are artificial for the first class and natural for the second.

Radio-frequency occultation experiments employing one (downlink) or two (downlink and uplink) communications frequencies have been described by Kliore and his colleagues (Reference 17). The first experiment does not involve a spacecraft sensor, since it requires only the spacecraft telecommunications system and the receiver on Earth. The second experiment requires a transponder on the spacecraft to process data representing the attenuation and phase shift of the uplink signal. Similar experiments could be performed between two spacecraft at the planet. The electron density lapse rate at Jupiter may be so small (possibly 5 to 10 km, as in the case of the neutral density just above the clouds) that little information other than the height of the upper edge of the ionosphere can be obtained. This information alone, however, would be of great interest.

Solar occultation in the visible and infrared can provide compositional data from Fraunhofer spectroscopy (Reference 18). Stellar occultations allow improved determination of planetary radii to the top of the atmosphere.

5.2.7 Miscellaneous Observations

Magnetic Diffusivity

When a magnetic field disturbance intercepts a satellite, the velocity of propagation of the disturbance through the satellite is a measure of the satellite's electrical conductivity (Reference 19). The time required for magnetic lines of force to diffuse through the satellite is

$$t_D = \mu \sigma r^2$$

where μ is the satellite's magnetic permeability, σ is its electrical conductivity, and r is its radius. The solar wind flows past the satellite in time

$$t_w = 2r/V_w$$

where V_w is the wind velocity relative to the satellite. A steady magnetic field near the satellite requires $t_D = t_W$, so that

$$\sigma = 2/\mu r\, V_w$$

Saturn's Rings

The general structure of Saturn's rings can be studied by optical imaging from a flyby or an orbiter; a search can be made for a division between the crepe (C) and second (B) ring, material in Cassini's division between rings A and B, a faint ring outside the la Roche limit (2.44 Saturn radii), the possible ring inside the crepe ring (Reference 20), and the like. Radio occultation experiments can be a sensitive indicator of sparse ring material. To investigate the composition, infrared and microwave spectroscopy can be used.

Infrared radiometric measurements as ring material enters and exits the umbra of Saturn may give some indication of the particle size and thermal capacity and conductivity. If, as Kuiper has recently reported (Reference 20), the ring particles are solid ammonia blocks several centimeters on an edge, microwave radiometry at 1.25 cm and longer wavelengths should verify both the composition and size estimates.

The use of two active spacecraft (e.g., a Saturn orbiter or a probe and a flyby vehicle going on to Uranus or Pluto) at Saturn encounter permits a unique experiment to measure the size and number of particles in the rings. The experiment requires an active microwave radar transmitter and receiver on the orbiter or probe and a receiver on the flyby vehicle (activated when the Saturn orbiter is separated). The beam is transmitted through the rings, with the following possible results:

1. The beam is completely interrupted, indicating thick, dense swarms of ring particles.

2. The beam is interrupted for brief instants, indicating occasional ring particles as large as the geometric beamwidth.

3. The beam is smoothly attenuated, indicating a thin population of small particles.

The reflected signal also indicates the distribution of particle sizes near the wavelength. Variants of the experiment with laser beams, incoherent light sources, and the like can easily be imagined.

5.3 OBSERVATION PARAMETERS

The final step in quantitative definition of planetary observation requirements is specification of the desirable and just-acceptable values of various parameters. These parameters refer to the intrinsic planetary property to be observed rather than to the measurement capability of a remote sensor. For example, spatial resolution at the planetary surface is an appropriate parameter, but angular resolution at the spacecraft location is not because it depends on the trajectory. Observation requirements will be translated into sensor measurement capability requirements in Phases 2 and 3 of the study.

5.3.1 Observation Types

To aid in establishing which parameters are relevant to a given observation and to assist (in Phases 2 and 3) in matching sensor types to observation requirements, candidate observation types have been listed in

Table 10. Observation Types

Number	Description
1	Radio flux measurement (nonimaging) (wavelengths longer than 1 cm)
2	Microwave radiometry (1 cm to 100 micron)
3	Infrared radiometry (100 to 0.7 micron)
4	Visible photometry (0.7 to 0.4 micron)
5	Ultraviolet photometry (0.4 micron to 100 A)
6	X-ray photometry (100 A to 0.1 A)
7	γ-ray flux measurement (<0.1 A, or photon energies >120 kev)
8	Multiband flux measurement
11	Radio-wave spectrometry
12	Microwave spectrometry
13	Infrared spectrometry
14	Visible spectrometry
15	Ultraviolet spectrometry
16	X-ray spectrometry
17	γ-ray spectrometry
18	Multiband spectrometry
21	Passive radio-wave imagery
22	Passive microwave imagery
23	Passive infrared imagery
24	Passive visible imagery
25	Passive ultraviolet imagery
26	Passive X-ray imagery
27	Passive γ-ray imagery
28	Passive multiband imagery
31	Monostatic radar (nonimaging)
32	Monostatic radar imagery
33	Bistatic radar (nonimaging)
34	Bistatic radar imagery
35	Laser transmission/reflection/scattering
36	Earth occultation (radio)
38	Other observations involving active artificial sources of electromagnetic radiation (e.g., another spacecraft)
39	Occultation of natural sources of electromagnetic radiation (e.g., stars)
41	Radio-wave polarimetry
42	Microwave polarimetry
43	Infrared polarimetry
44	Visible polarimetry
45	Ultraviolet polarimetry
46	X-ray polarimetry
47	γ-ray polarimetry
48	Multiband polarimetry
51	Magnetic field measurement
52	Electric field measurement
53	Charged particle (electrons, protons, and heavy nuclei) flux or dose measurement
54	Charged particle spectrometry
55	Neutral particle (neutrons) flux or dose measurement
56	Neutral particle spectrometry
57	Auroral and airglow emission spectrometry*
58	Microwave tracking
99	Other observation types

*Special case of types 14 and 15.

Table 10. These types are distinguished by wavelength and kind of measurement (radiometry and photometry, spectrometry, imagery, radar and laser experiments, occultation experiments, polarimetry, and particle and field measurements). The observation types are, therefore, closely correlated with observable properties and also with candidate sensor instrument categories. The wavelength regions for each kind of measurement are indicated for the radiometry and photometry types.

These observation techniques are only guides to the later identification of applicable sensor types, and serve mainly to exclude grossly inapplicable sensors. Actual identification of sensors will be based on a detailed comparison of observation requirements with measurement capabilities. It may result that portions of an observation can be accomplished by different sensors, although no one sensor can perform all of the observation. For example, a microwave radiometer (electronic) could cover part of a spectral region, and an infrared radiometer (optical) another part.

In the top-down approach example, the observation of electromagnetic phase shift and attenuation is clearly suited to a bifrequency radio occultation experiment employing command (uplink) and telemetry (downlink) frequencies, with a transponder on the spacecraft.

5.3.2 Observation Parameter Definition

The observation parameters and their units are listed in Table 11. Any of the first 15 parameters and any five of the remaining 25 may be used to describe a given observation. It was never necessary to use more than 4 of the last 25 parameters in any one case.

If the i^{th} parameter is relevant to an observation, its "best" (most stringent desired) value a_i', its "worst" (least stringent acceptable) value a_i'', its maximum worth $w_i(a_i')$, and the functional form of $w_i(a_i)$ for values of a_i between a_i' and a_i'' are specified. It must be indicated whether greater or smaller values of a_i represent a more stringent requirement, i.e., whether $a_i' > a_i''$ or $a_i'' > a_i'$. If a_i is poorer than a_i'', $w_i(a_i) = 0$. If a_i is better than a_i', usually $w_i(a_i) = w_i(a_i')$, but provision can be made for $w_i(a_i) > w_i(a_i')$ in this case. In all cases, $0 \le w_i(a_i) \le 1$. The allowed forms of $w_i(a_i)$ are defined in Appendix D; these forms are linear, trigonometric, exponential, step, delta, and square-wave functions of a_i or $\log_{10}|a_i|$.

The observation requirements in the example (Table 2) are explained as follows. The experiment is to be performed at two communications frequencies; the lower of these should correspond to a 75-cm or longer wavelength, with 1.7 meters desired. The higher frequency should correspond to a wavelength of 13 cm or longer, with 3.5 cm desired. The lower

Table 11. Observation Parameters

No.	Definition	Unit
1	Longest wavelength of spectral region	Micron
2	Shortest wavelength of spectral region	Micron
3	Spectral resolution, at wavelength requiring highest resolution	Micron
4	Spatial resolution at target	Meter
5	Fraction of surface area of planet covered	Percent
6	Northernmost latitude of area covered (negative if in northerm hemisphere)	Degree
7	Southernmost latitude of area covered (negative if in northern hemisphere)	Degree
8	Maximum Sun elevation angle above horizon at target	Degree
9	Minimum Sun elevation angle above horizon	Degree
10	Vertical resolution	Meter
11	Maximum altitude of observed property (above surface at Mercury and Mars; above visible cloud tops at other planets)	Meter
12	Minimum altitude of observed property	Meter
13	Number of observations or samples	---
14	Time elapsed during one observation	Second
15	Interval between commencement of two successive observations	Second
16	Intensity resolution (gray scale, spectral line strength, field strength, and particle flux)	Percent of maximum intensity
17	Planetocentric angle from planet center-to-spacecraft line	Degree
18	Angle at planet surface from surface element-to-spacecraft line	Degree
19	Angular resolution	Degree
20	Phase shift precision	Degree
21	Polarization (amount)	Percent
22	Rotation angle of plane of polarization (positive counter-clockwise)	Degree
23	Albedo	Percent
24	Magnetic field strength	Oersted
25	Electric field strength	Volt m^{-1}
26	Gravitational acceleration	m sec^{-2}
27	Particle flux	m^{-2} sec^{-1}
28	Particle or photon energy	Electron volt
29	Electromagnetic energy flux	Watt m^{-2}
30	Maximum temperature	°K
31	Minimum temperature	°K
32	Temperature resolution	°K
33	Maximum pressure	Bar
34	Minimum pressure	Bar
35	Pressure resolution	Bar
36	Velocity	m sec^{-1}
37	Longitude (east of central meridian seen from Earth except standard areographic coordinates are used at Mars)	Degree
38	Latitude interval	Degree
39	Longitude interval	Degree
40	Other than above	Degree

frequency is characteristic of the uplink signal, and the higher frequency corresponds to S-band or X-band telemetry to Earth. Any latitude is acceptable, but coverage of all latitudes is desired. Likewise, any solar elevation at the occulting limb is acceptable, but all elevations should be covered to allow investigation of diurnal variations in the ionosphere. The occultation data should be acquired once each 0.01 to 1 second, to allow adequate definition of the altitude profile with a typical spacecraft trajectory. The attenuation of the occulted signals should be measured to a precision of at least 1 db, and preferably 0.1 db. The phase shift should be determined to a precision of 1 cycle to 0.1 cycle. Any single observation is of value, but it is desirable to cover all latitudes in 10-degree intervals, and all planetographic (co-rotating) longitudes in 45-degree intervals.

Some of the observation parameter definitions in Table 11 are unambiguous, but others require clarification with regard to their use in the observation requirements specifications.

Longest and Shortest Wavelengths of Spectral Region (Parameters 1, 2)

The longest wavelength λ_M and the shortest wavelength λ_m are specified independently in the ranges $\lambda''_M \leqq \lambda_M \leqq \lambda'_M$ and $\lambda'_m \leqq \lambda_m \leqq \lambda''_m$, respectively. $\lambda_M \geqq \lambda_m$, even if $\lambda''_M < \lambda''_m$, where single primes refer to the desired observation capability, and double primes to the poorest acceptable capability.

Spectral Resolution (3)

Usually $\Delta\lambda/\lambda$ is constant, so $\Delta\lambda$ is minimum at $\lambda = \lambda'_m$. In a spectroscopic observation, the entire spectral region is to be covered at the indicated $\Delta\lambda/\lambda$. In other observations, a single band of width $\Delta\lambda$ is to be selected, centered at any λ in $\lambda_M \geqq \lambda + \Delta\lambda/2 > \lambda - \Delta\lambda/2 \geqq \lambda_m$. If several non-contiguous bands are to be covered, a separate ORDS is generated for each band.

Spatial Resolution at Target (4)

In imaging observations, this is the resolution of image elements. Otherwise, it is the resolution of the entire frame considered as a single element.

Northernmost and Southernmost Latitude (6, 7)

This situation is similar to longest and shortest wavelength. Figure 4 illustrates a case where northern latitudes from the equator to 40 degrees must be covered, and coverage up to 60 degrees is desired. In the southern hemisphere, minimum acceptable coverage is 0 to 30 degrees, with 0 to 60 degrees desired.

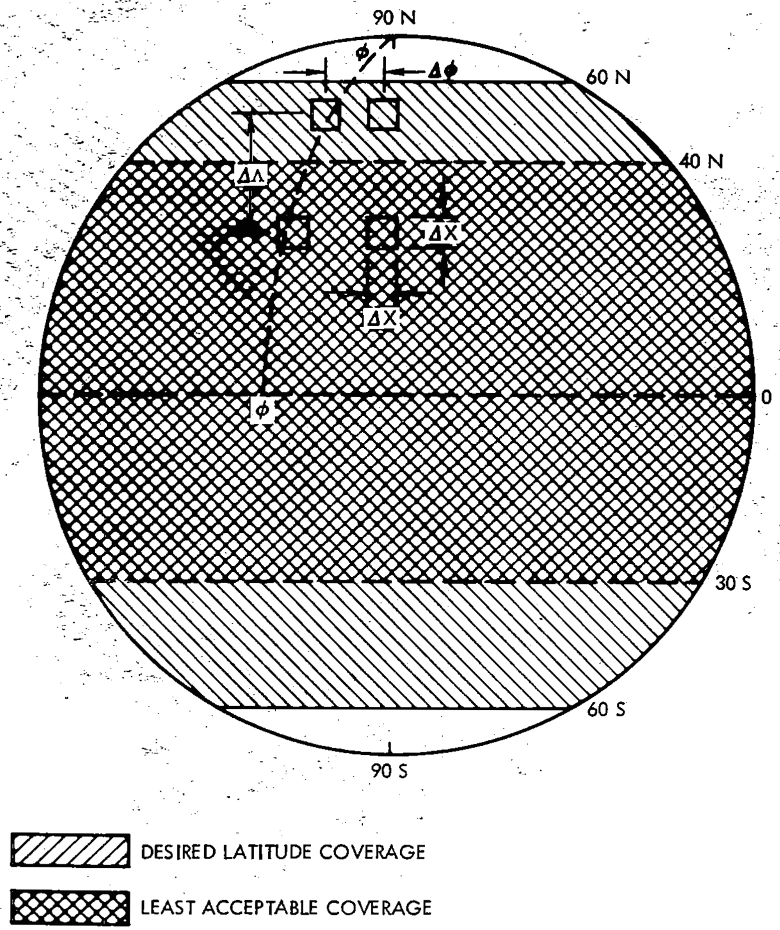

Figure 4. Latitude and Longitude Coverage and Intervals

Number of Observations (13)

In cases of imagery, a sample consists of one frame. This parameter is specified only when it is of intrinsic importance, e.g., related to statistical accuracy of the results. Determination of the number and size of frames needed to cover a given total area depends on the mission trajectory and the sensor design.

Time Elapsed During One Observation (14)

This is the "shutter speed," specified only when it is necessary to determine, to a given precision, the instantaneous value of a time-dependent quantity.

Albedo (23)

The various albedo measures (Bond, bolometric, etc.) are not distinguished here (see discussion by G. deVaucouleurs in Appendix B).

Latitude and Longitude Intervals (38, 39)

These quantities refer to the separation of centers of adjacent viewed areas. In imaging observations, the areas must touch or overlap to form a complete image. In other observations, the areas overlap if

$$(\cos \bar{\Lambda})\ (\Delta\phi) \leq R_p\ \Delta X$$

or

$$\Delta\Lambda < R_p\ \Delta X$$

where $\bar{\Lambda}$ is the mean latitude, $\Delta\Lambda$ is the latitude interval, $\Delta\phi$ is the longitude interval, R_p is the planetary radius, and ΔX is the spatial resolution (see Figure 4).

5.4 OBSERVATION REQUIREMENTS SUMMARY

Table 12 is a condensed summary of the observation requirements. It indicates the relevant associations of goals, knowledge requirements, observation objectives, observable properties, observation techniques, and planet. The table is arranged with inner-planet observations first, observations common to inner and outer planets next, and outer-planet observations last. Each set of observations is arranged in order of decreasing wavelength. Page numbers refer to the detailed requirements data in Appendix C.

Table 12. Summary of Observation Requirements

Pages	Goal	Knowledge Requirement	Observation Objective: Number	Observation Objective: Worth	Sub-Objective Description	Observable: Number	Observable: Technique	Observable: Worth	Sub-Observable Description	Planets**
C-27	1*	11	6	0.99	Total thermal emission of planetary disk	15	2	0.80	Effective average thermal radiation of disk	1, 4*
	3		6	0.99	Total thermal emission of planetary disk	15	2	0.80	Effective average thermal radiation of disk	1, 4
C-28, C-29	5*	4	12	0.70	Physical properties for engineering model atmospheres	16	12	0.60	Microwave emission spectrum	2
C-30, C-31	5*	4	13	0.70	Physical properties for engineering model atmospheres	15	2	0.50	Microwave thermal emission flux	2
C-32, C-33	5*	4	13	0.70	Physical properties for engineering model atmospheres	17	3	0.60	IR thermal emission flux	2
C-34, C-35	5*	4	12	0.70	Physical properties for engineering model atmospheres	18	13	0.60	IR absorption spectra	2
C-36	1*	11	9	0.99	Total thermal emission of planetary disk	17	3	0.80	Effective average thermal radiation of disk	1, 4*
	3	11	9	0.99	Total thermal emission of planetary disk	17	3	0.80	Effective average thermal radiation of disk	1, 4
C-37	4*	13	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1*, 4
	4	24	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
	4	26	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
	5	13	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
	5	24	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
	5	26	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
C-38, C-39	5*	4	12	0.50	Physical properties for engineering model atmosphere	20	15	0.50	UV absorption and emission spectra	2
C-40	1*	7	7	0.99	Elemental composition of surface material	43	16	0.50	X-ray spectrum induced by solar bombardment	1
C-41	1*	7	7	0.99	Elemental and isotopic composition of surface material	12	17	0.70	Gamma-ray spectrum (decay and cosmic ray induced)	1*, 4
C-42	1*	7	17	0.99	Neutral radioactivity of surface material	13	54	0.80	Alpha spectrum from parent, daughter nuclides	1
C-43	1*	7	17	0.99	Hydrogen/silicon ratio at surface	44	55	0.40	Fast/slow albedo neutron flux ratio	1
C-44	1*	10	6	0.30	Planet interior electrical conductivity	11	51	0.50	Solar wind proton flux	1
C-45	1*	4	12	0.75	General information about planetary ionospheres	12	31	0.50	Radar echo versus time	2, 5*, 6, 7, 8
C-46	1*	4	12	0.80	Ionosphere electron density profile	27	41	0.65	RF reflectivity/signal return time	1, 2, 4, 5*, 6, 7, 8
	5	4	12	0.80	Ionosphere electron density profile	27	41	0.65	RF reflectivity/signal return time	1, 2, 4, 5, 6, 7, 8
	4	24	12	0.80	Ionosphere electron density profile	27	41	0.65	RF reflectivity/signal return time	1, 2, 4, 5, 6, 7, 8
C-47	1*	12	18	0.80	Thermal/nonthermal planetary emissions	21	1	0.80	Radio emissions	1, 2, 4, 5, 6*, 7, 8
	3	12	18	0.80	Thermal/nonthermal planetary emissions	21	1	0.80	Radio emissions	1, 2, 4, 5, 6, 7, 8
C-48, C-49	1*	4	13	0.85	Neutral ion, electron density profiles in atmosphere	12	36	0.85	Bi-frequency radio occultation	1, 2, 4, 5*, 6, 7, 8
	3	4	13	0.85	Neutral ion electron density profiles in atmosphere	12	36	0.85	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	5	4	13	0.99	Neutral ion, electron density profiles in atmosphere	12	36	0.85	Bi-frequency radio occultation*	1, 2, 4, 5, 6, 7, 8
C-50	3*	5	14	0.80	Heat balance in lower atmosphere	15	2	0.80	Microwave emissions (thermal)	2, 5*, 6, 7, 8
	5	5	14	0.80	Heat balance in lower atmosphere	15	2	0.80	Microwave emissions (thermal)	2, 5, 6, 7, 8
C-51	3*	5	14	0.80	Heat balance at surface and below clouds	15	2	0.80	Microwave emissions (thermal)	2, 4, 5*, 6, 7, 8
	5	5	14	0.80	Heat balance at surface and below clouds	15	2	0.80	Microwave emissions (thermal)	2, 4, 5, 6, 7, 8
C-52	5	4	13	0.70	Physical properties for engineering model atmospheres	15	2	**	Microwave thermal emission flux	1, 4(0.5), 5, 6, 7, 8 [illegible]
C-53	1*	7	11	0.80	Planet surface dielectric properties	15*	42	0.80	Polarization of microwave thermal emissions	1, 2, 4, 5, 6*, 7, 8
	3	7	11	0.80	Planet surface dielectric properties	40	42	0.80	Polarization of microwave thermal emissions	1, 2, 4, 5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis

Table 12. Summary of Observation Requirements (Cont)

Pages	Goal	Knowledge Requirement	Observation Objective: Number	Observation Objective: Worth	Sub-Objective Description	Observable: Number	Observable: Technique	Observable: Worth	Sub-Observable Description	Planets**
C-54	1*, 3	4*	9*	0.90	Microwave thermal emission	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
	1, 3	4*	13	0.99	Physical properties for engineering model atmosphere	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
	1, 3	4*	21	0.30	Microwave thermal emissions	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
	1, 3	4*	22	0.50	Microwave thermal emissions	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
	1	5	9	0.30	Microwave thermal emission	15	2	0.90	Thermal emission measurement by radiometry	2, 4, 5, 6, 7, 8
	1	5	13	0.80	Physical properties for engineering model atmosphere	15	2	0.90	Thermal emission measurement by radiometry	2, 4, 5, 6, 7, 8
	1	11	9	0.99	Microwave thermal emission	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6, 7, 8
C-55	1, 2*	1*	12*	0.80	Abundance of NH_3, NH_2O, H_2O, H/D ratio	16	12	0.80	Microwave spectrum	2, 4, 5, 6*, 7, 8
	1, 2	2, 3	12	0.30	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	2, 4
	1, 2	2, 3	13	0.70	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	2, 4
	1	4	12	0.99	Physical properties of engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
	1	4	13	0.99	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
	1	6	12	0.90	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
	1	6	13	0.80	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
C-56	1*	4	12	0.90	Atmospheric composition	16	2	0.40	Microwave thermal emission spectrum w/absorption	2, 5*, 6, 7, 8
	5	4	12	0.90	Atmospheric composition	16	2	0.40	Microwave thermal emission spectrum w/absorption	2, 5*, 6, 7, 8
C-57	4*	9	1	0.90	Size, shape, motion of planet	24	35	0.90	Laser beam reflectivity	1*, 4, 6 (rings only)
	5	9	1	0.90	Size, shape, motion of planet	24	35	0.90	Laser beam reflectivity	1, 4, 6 (rings only)
C-58	1*	4	12	0.90	Brightness temperature over wide frequency range	17	3	0.90	IR thermal emission	1, 2, 5*, 6, 7, 8
C-60, C-61	5*	4	13	0.70	Physical properties for engineering model atmosphere	17	3	0.60	IR thermal emission flux	1, 5*, 6, 7, 8
C-62	3*	5	14	0.80	Heat balance at and beneath clouds	17	3	0.80	IR radiation flux	2, 4, 5*
	5	5	14	0.80	Heat balance at and beneath clouds	17	3	0.80	IR radiation flux	2, 4, 5
C-63	3*	5	14	0.80	Heat balance in atmosphere	17	3	0.80	IR radiation flux	2, 4, 5*, 6, 7, 8
	5	5	14	0.80	Heat balance in atmosphere	17	3	0.80	IR radiation flux	2, 4, 5, 6, 7, 8
C-64	1*	4	12	0.90	Cloud composition	18	13	**	IR absorption spectra	2(0.4), 4(0.2); 5*, 6, 7, 8(0.7)
	5	4	12	0.90	Cloud composition	18	13	**	IR absorption spectra	2(0.4), 4(0.2); 5, 6, 7, 8(0.7)
C-65	1*	4	12	0.85	Trace substances in atmosphere and clouds	20	18	0.80	IR/visible/UV spectra	2, 5*, 6, 7, 8
	3	4	12	0.85	Trace substances in atmosphere and clouds	20	18	0.80	IR/visible/UV spectra	2, 5, 6, 7, 8
	5	4	12	0.85	Trace substances in atmosphere and clouds	20	18	0.80	IR/visible/UV spectra	2, 5, 6, 7, 8
C-66	1*	4	14	0.50	Aerosol size distribution in atmosphere	24	35	0.50	Laser scattering, transmission in atmosphere	2, 4, 5*, 6, 7, 8
C-67	3*	4	28	0.50	Radiation scattering properties of cloud tops	18	13	0.40	IR radiation (spectrum)	2, 5*, 6, 7, 8
C-68	3*	4*	28	0.50	Radiation scattering properties of cloud tops	17	3	0.30	IR radiation (flux)	2, 4, 5*, 6, 7, 8
	3	5	28	0.30	Radiation scattering properties of cloud tops	17	3	0.30	IR radiation (flux)	2, 4, 5, 6, 7, 8
C-69	3*	4*	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5*, 6, 7, 8
	3	5	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5, 6, 7, 8
	5	4	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5, 6, 7, 8
	5	5	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5, 6, 7, 8
C-70	3*	4*	28	0.50	Radiation scattering properties of cloud tops	19	4	0.80	Visible/UV radiation (flux)	2, 4, 5*, 6, 7, 8
	3	5	28	0.50	Radiation scattering properties of cloud tops	19	4	0.80	Visible/UV radiation (flux)	2, 4, 5, 6, 7, 8
C-71	1*	4*	12	0.90	Hydrogen abundance	20	5	0.90	Lyman alpha line for hydrogen	1, 2, 4, 5*, 6, 7, 8
	1	6	12	0.90	Hydrogen abundance	20	5	0.90	Lyman alpha line for hydrogen	1, 2, 4, 5, 6, 7, 8
	3	6	12	0.90	Hydrogen abundance	20	5	0.90	Lyman alpha line for hydrogen	1, 2, 4, 5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parentheses

Table 12. Summary of Observation Requirements (Cont)

Pages	Goal	Knowledge Requirement	Observation Objective Number	Observation Objective Worth	Sub-Objective Description	Observable Number	Technique	Observable Worth	Sub-Observable Description	Planets**
C-72	4	24	16	0.80	Planet interior structure and motions	9*, 10	51	0.90	Magnetic field distribution above surface	1*, 5, 6, 7, 8
	4	2[illegible]	16	0.80	Planet interior structure and motions	9, 10	51	0.90	Magnetic field distribution above surface	1, 5, 6, 7, 8
	[illegible]	24	16	0.80	Planet interior structure and motions	9, 10	51	0.90	Magnetic field distribution above surface	1, 5, 6, 7, 8
	[illegible]	2[illegible]	16	0.80	Planet interior structure and motions	9, 10	51	0.90	Magnetic field distribution above surface	1, 5, 6, 7, 8
	4	24	1[illegible]	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
	4	[illegible]	15	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
	4	1[illegible]	16	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
	[illegible]	25	14	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
C-74	[illegible]	[illegible]	5	0.40	Altitude variation over solid surface	12	36	0.40	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	[illegible]	[illegible]	10	0.50	Planetary surface definition-surface topography	12	36	0.40	Bi-frequency radio occultation	4
	[illegible]	[illegible]	21	0.20	RF reflectivity characteristics	12	36	0.40	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
C-75	1	4	22	0.30	RF occultation characteristics	12, 1[illegible]	36	0.40	Bi-frequency radio occultation	4
	1	4	12	0.90	Atmosphere charged particle density	12, 19	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1	4	21	0.40	RF reflectivity characteristics	12, 39	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1	4	22	0.50	RF occultation characteristics	12, 39	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1, 3	5	14	0.99	Atmosphere circulation	12	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1, 3	5	21	0.20	RF reflectivity characteristics	12, 39	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1	13	17	0.40	Particle radiation	39	36	0.90	Bi-frequency radio occultation	5, 6, 7, 8
	1	13	18	0.30	Thermal/nonthermal planetary emissions	19	36	0.90	Bi-frequency radio occultation	5, 6, 7, 8
C-76	1, 3	4	19	0.70	Density discontinuities	12	36	0.70	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1, 3	7	15	0.70	Density discontinuities	12	36	0.70	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
	1	7	21	0.90	RF reflectivity characteristics	12	36	0.70	Bi-frequency radio occultation	4, 5, 6, 7, 8
	1	7	22	0.20	RF occultation characteristics	32	36	0.70	Bi-frequency radio occultation	[illegible]
C-77	3	4	13	0.50	Transparency of atmosphere to RF radiation	21	1[illegible]	[illegible]	Transmitted RF radiation from Sun vs impact parameter	5 (0.5), 6 (0.3), 7 (0.15), 8 (0.07)
	3	21	13	0.50	Transparency of atmosphere to RF radiation	21	1[illegible]	[illegible]	Transmitted RF radiation from Sun vs impact parameter	5 (0.5), 6 (0.3), 7 (0.15), 8 (0.07)
C-78	3	13	18	0.50	Sources of non-thermal planetary RF emissions	21	1[illegible]	0.50	RF radiations from planet	5, 6, 7, 8
C-79	1	17	24	0.30	Saturn ring particle size and composition	21	1[illegible]	0.50	Radio absorption and reflection vs wavelength	6 (rings only)
C-80	5	4	12	0.70	Physical properties for engineering model atmospheres	16	13	0.60	Microwave emission spectrum	5, 6, 7, 8
C-81	1	4	13	0.75	Atmospheric pressure profile	18	13	0.25	High resolution IR spectroscopy of NH_3	6
C-82	1	4	13	0.70	H/D isotopic abundance in atmosphere	18	13	0.70	Far IR spectroscopy to detect CH_3D, NH_2D, HD	5, 6, 7, 8
C-83	1	4	13	0.90	Far IR planetary thermal emissions	17	1[illegible]	0.90	Far IR emissions (100μ - 10μ)	5, 6, 7, 8
	2	4	13	0.90	Far IR planetary thermal emissions	17	1[illegible]	0.90	Far IR emissions (100μ - 10μ)	5, 6, 7, 8
C-84	5	4	12	0.70	Physical properties of engineering model atmospheres	18	13	0.60	IR absorption spectra	5, 6, 7, 8
C-85	3	4	13	0.80	Transparency of atmosphere	19	19	[illegible]	Sunlight flux versus impact parameter	5 (0.8), 6 (0.5), 7 (0.[illegible]), 8 (0.15)
C-86	1	15	1[illegible]	0.50	Saturn ring particle distribution	17	20	0.30	Flux of sunlight transmitted	6 (rings only)
C-87	1	4	13	0.60	Atmospheric pressure profile	18	13	0.60	High resolution IR spectroscopy of NH_3, CH_4	5, 6, 7, 8
C-88	5	4	13	0.90	Physical properties for engineering model atmospheres	18	13	0.90	High resolution IR spectroscopy of NH_3, CH_4	5, 6, 7, 8
C-89	1	4	12	0.70	Hydrogen abundance	18	13	0.60	Pressure-induced spectrum of hydrogen overtones	5, 6, 7, 8
C-90	1	11	13	0.90	Planetary Bond albedo	19	4	0.90	Photometric measurement in the visible	5, 6, 7, 8
	1	11	21	0.70	RF reflectivity characteristics	19	4	0.70	Photometric measurement in the visible	5, 6, 7, 8
C-91	1	4	12	0.40	Hydrogen abundance	18	13	0.40	Pressure-induced spectrum of hydrogen overtones	5, 6, 7, 8
C-92, C-93, C-94, C-95	1	4	12	0.50	Atmospheric properties above magnetic poles	20	15	[illegible]	Optical photon spectrum from polar aurorae	5*(0.25), 6(0.2), 7(0.15), 8(0.[illegible])

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parentheses

Table 12. Summary of Observation Requirements (Cont)

Pages	Goal	Knowledge Requirement	Observation Objective Number	Observation Objective Worth	Sub-Objective Description	Observable Number	Technique	Observable Worth	Sub-Observable Description	Planets**
C-96	3*	4*	18	0.55	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5*, 6, 7, 8
	3	6	18	0.70	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
	3	13	18	0.20	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
	3	18	18	0.30	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
	3	24	18	0.60	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
C-97	1*	4	12	0.70	Methane abundance	20	14	0.70	Methane absorption spectra	5*, 6, 7, 8
C-98	1*	4	12	0.30	H/D ratio	20	14	**	HD and H_2 absorption spectra	5*(0.3), 6(0.2); 7, 8(0.1)
C-99	1*	4	12	0.30	H/D ratio	20	15	**	HD and H_2 absorption spectra	5*(0.3), 6(0.2); 7, 8(0.1)
C-100	1*	17	24*	0.30	Saturn ring particle density	41	4	0.30	Stellar occultation (photometric)	6
	1	17	22	0.20	RF occultation characteristics	41	4	0.30	Stellar occultation (photometric)	6
C-101	3*	4*	13	0.50	Transparency of atmosphere to RF radiation	21	39	**	Transmitted RF radiation from Sun vs impact parameter	5*(0.5), 6(0.3), 7(0.15), 8(0.07)
	3	21	13	0.70	Transparency of atmosphere to RF radiation	21	39	**	Transmitted RF radiation from Sun vs impact parameter	5(0.5), 6(0.3), 7(0.15), 8(0.07)
C-102	1*	4	12	0.70	Ammonia abundance	20	14	0.70	Ammonia absorption spectra	5
C-103	5*	15	12*	0.50	Upper atmosphere composition	19	5	0.30	UV light emitted from meteoroid trails	5*, 6, 7, 8
	5	15	23	0.20	Meteoroid environment	19	5	0.30	UV light emitted from meteoroid trails	5, 6, 7, 8
C-104	1	4	12	0.60	Trace constituents of purines, pyrimidines	20	15	0.60	UV absorption spectra	5, 6*, 7, 8
	2*	4	12	0.60	Trace constituents of purines, pyrimidines	20	15	0.60	UV absorption spectra	5, 6, 7, 8
C-105	5*	4	12	0.70	Physical properties for engineering model atmospheres	20	15	0.50	UV absorption, emission spectra	5*, 6, 8
C-106	5*	4	12	0.70	Physical properties for engineering model atmospheres	20	15	0.50	UV absorption, emission spectra	7
C-107	1*	4*	12	0.90	Helium abundance, He/H ratio	20	5	0.90	Helium resonance lines	5*, 6, 7, 8
	1	6	12	0.90	Helium abundance, He/H ratio	20	5	0.90	Helium resonance lines	5, 6, 7, 8
	3	4	12	0.90	Helium abundance, He/H ratio	20	5	0.90	Helium resonance lines	5, 6, 7, 8
C-108	3*	12	6*	0.75	Planetary interior composition	10	51	0.75	Magnetic field components as a function of position	5*, 6, 7, 8
	1	12	16	0.40	Planetary interior structure	10	51	0.75	Magnetic field components as a function of position	5, 6, 7, 8
C-109	4*	22*	10	0.50	Planetary surface definition-surface topography	2	32	0.10	Microwave imaging	5, 6*, 7, 8
	5	3	10	0.20	Planetary surface definition-surface topography	2	32	0.10	Microwave imaging	5, 6, 7, 8
	5	8	10	0.30	Planetary surface definition-surface topography	2	32	0.10	Microwave imaging	5, 6, 7, 8
	5	22	10	0.50	Planetary surface definition-surface topography	2	32	0.10	Microwave imaging	5, 6, 7, 8
C-110	1*	5*	9*	0.30	Formation of large diameter particles in clouds	27	31	0.25	Radar echo vs time	5*, 6, 7, 8
	1	5	14	0.90	Atmospheric circulation	27	31	0.40	Radar echo vs time	5, 6, 7, 8
	1	5	15	0.70	Atmospheric heat balance	27	31	0.40	Radar echo vs time	5, 6, 7, 8
	1	6	9	0.20	Thermal emission from planetary disk	27	31	0.05	Radar echo vs time	5, 6, 7, 8
	1	8	9	0.40	Thermal emission from planetary disk	27	31	0.05	Radar echo vs time	5, 6, 7, 8
	2	2	15	0.30	Atmospheric heat balance	27	31	0.20	Radar echo vs time	5, 6, 7, 8
	2	3	15	0.30	Atmospheric heat balance	27	31	0.20	Radar echo vs time	5, 6, 7, 8
	3	4	14	0.90	Atmospheric circulation	27	31	0.25	Radar echo vs time	5, 6, 7, 8
	3	4	15	0.70	Atmospheric heat balance	27	31	0.40	Radar echo vs time	5, 6, 7, 8
	3	5	14	0.90	Atmospheric circulation	27	31	0.25	Radar echo vs time	5, 6, 7, 8
C-111	4*	9*	1	0.90	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)
	4	21	1	0.20	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)
	5	9	1	0.90	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)
	5	21	1	0.30	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parentheses

Table 12. Summary of Observation Requirements (Cont)

Pages	Goal	Knowledge Requirement	Observation Objective Number	Observation Objective Worth	Sub-Objective Description	Observable Number	Observable Technique	Observable Worth	Sub-Observable Description	Planets**
C-112	1	5*	9*	0.30	Thermal emission from planetary surface	27	22	0.30	Spatial variation of microwave emissivity	5*, 6, 7, 8
	1	5	14	0.90	Atmospheric circulation	27	22	0.30	Spatial variation of microwave emissivity	5*, 6, 7, 8
	1	5	15	0.70	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	1	6	9	0.20	Thermal emission from planetary disk	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	1	8	4	0.40	Thermal emission from planetary disk	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	2	2	15	0.30	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	2	3	15	0.30	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	3	4	14	0.90	Atmospheric circulation	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	3	4	15	0.70	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
	3	5	14	0.90	Atmospheric circulation	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
C-113	1	5*	9*	0.30	Surface temperature, heat transfer	27	32	0.50	Microwave imaging	5*, 6, 7, 8
	1	5	14	0.30	Atmospheric circulation	27	32	0.50	Microwave imaging	5, 6, 7, 8
	1	5	15	0.70	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
	1	6	9	0.20	Surface temperature, heat transfer	27	32	0.50	Microwave imaging	5, 6, 7, 8
	1	8	9	0.40	Surface temperature, heat transfer	27	32	0.50	Microwave imaging	5, 6, 7, 8
	2	2	15	0.30	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
	2	3	15	0.30	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
	3	4	14	0.90	Atmospheric circulation	27	32	0.50	Microwave imaging	5, 6, 7, 8
	3	4	15	0.70	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
	3	5	14	0.90	Atmospheric circulation	27	32	0.50	Microwave imaging	5, 6, 7, 8
C-114	1	5*	9*	0.30	Surface temperature, heat transfer	27	42	0.20	Polarization of microwave thermal emissions	5*, 6, 7, 8
	1	5	14	0.90	Atmospheric circulation	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	1	5	15	0.70	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	1	6	9	0.20	Surface temperature, heat transfer	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	1	8	9	0.40	Surface temperature, heat transfer	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	2	2	15	0.30	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	2	3	15	0.30	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	3	4	14	0.90	Atmospheric circulation	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	3	4	15	0.70	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
	3	5	14	0.90	Atmospheric circulation	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
C-115	4	22*	10	0.50	Planetary surface definition-surface topography	2	2	0.20	Microwave imaging	5, 6*, 7, 8
	5	3	10	0.20	Planetary surface definition surface topography	2	2	0.20	Microwave imaging	5, 6, 7, 8
	5	3	10	0.30	Planetary surface definition surface topography	2	2	0.20	Microwave imaging	5, 6, 7, 8
	5	22	10	0.50	Planetary surface definition surface topography	2	2	0.20	Microwave imaging	5, 6, 7, 8
C-116	4	22*	10	0.50	Planetary surface definition surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6*, 7, 8
	5	3	10	0.20	Planetary surface definition surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6, 7, 8
	5	3	10	0.30	Planetary surface definition surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6, 7, 8
	5	22	10	0.50	Planetary surface definition surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6, 7, 8
C-118, C-119	1	5	9*	0.90	Surface temperature, heat transfer	17	23	0.30	IR radiation from planetary surface	5*, 6, 7, 8
	1	5	13	0.80	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	1	5	14	0.90	Atmospheric circulation	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	1	4	13	0.99	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	1	6	4	0.30	Interior energy flow	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	1	6	9	0.40	Surface temperature, heat transfer	17	23	0.10	IR radiation from planetary surface	5, 6, 7, 8
	2	3	13	0.20	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	3	4	13	0.90	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	3	5	14	0.99	Atmospheric circulation	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	3	7	6	0.20	Internal physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
	1	11	4	0.60	Interior energy flow	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parentheses

Table 12. Summary of Observation Requirements (Cont)

Pages	Goal	Knowledge Requirement	Observation Objective Number	Observation Objective Worth	Sub-Objective Description	Observable Number	Observable Technique	Observable Worth	Sub-Observable Description	Planets**
C-120	1*	11*	4*	0.70	Interior energy flow	17	23	0.40	IR radiation from planetary surface	5*, 6, 7, 8
	1	5	9	0.80	Thermal emission from planetary disk	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
	1	5	14	0.90	Atmospheric circulation	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
	1	6	4	0.30	Interior energy flow	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
	1	6	9	0.40	Surface temperature, heat transfer	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
	3	5	14	0.99	Atmospheric circulation	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
	3	7	6	0.20	Internal physical properties	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
	3	11	4	0.60	Interior energy flow	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
C-121	1*	11*	4*	0.70	Interior energy flow	17	3	0.30	IR thermal emission	5*, 6, 7, 8
	1	5	9	0.80	Surface temperature, heat transfer	17	3	0.30	IR thermal emission	5, 6, 7, 8
	1	5	14	0.90	Atmospheric circulation	17	3	0.30	IR thermal emission	5, 6, 7, 8
	1	6	4	0.30	Interior energy flow	17	3	0.30	IR thermal emission	5, 6, 7, 8
	1	6	9	0.40	Surface temperature, heat transfer	17	3	0.30	IR thermal emission	5, 6, 7, 8
	3	5	14	0.99	Atmospheric circulation	17	3	0.30	IR thermal emission	5, 6, 7, 8
	3	7	6	0.20	Internal physical properties	17	3	0.30	IR thermal emission	5, 6, 7, 8
	3	11	4	0.60	Interior energy flow	17	3	0.10	IR thermal emission	5, 6, 7, 8
C-122	1*	9	1	0.30	Planetary diameter and figure	1	24	0.30	IR radiation from planet albedo	5
	5	9	1	0.40	Planetary diameter and figure	1	24	0.30	IR radiation from planet albedo	5
C-123	1*	9	1	0.10	Planetary diameter and figure	1	24	0.40	Optical diameter of disk	6
	5	9	1	0.40	Planetary diameter and figure	1	24	0.40	Optical diameter of disk	6
C-124	1*	9	1	0.30	Planetary diameter and figure	1	24	0.60	Optical diameter of disk	7*, 8
	5	9	1	0.30	Planetary diameter and figure	1	24	0.60	Optical diameter of disk	7, 8
C-125	3*	5	15	0.60	Atmospheric heat balance	1	28	0.70	IR/Visible/UV images of atmosphere	7
C-126	3*	5	15	0.60	Atmospheric heat balance	1	28	0.70	IR/Visible/UV images of atmosphere	5, 6, 8*
C-127	1*	11*	14*	0.80	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6*, 7, 8
	1	6	14	0.20	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6, 7, 8
	1	8	14	0.20	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6, 7, 8
	1	8	15	0.30	Atmospheric heat balance	1	24	0.80	Optical imaging	5, 6, 7, 8
	3	5	14	0.99	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6, 7, 8
	3	5	15	0.90	Atmospheric heat balance	1	24	0.80	Optical imaging	5, 6, 7, 8
C-128	3*	5	14	0.60	Cloud structure, precipitation forms	1	24	0.40	Optical imaging of clouds	5, 6*, 7, 8
C-129	1*	17	24	0.10	Saturn ring properties	1	24	0.50	Optical imaging of rings	6 (rings only)
	4	17	24	0.40	Saturn ring properties	1	24	0.50	Optical imaging of rings	6 (rings only)
	5	17	24	0.30	Saturn ring properties	1	24	0.50	Optical imaging of rings	6 (rings only)
C-130	3*	5	14*	0.80	Cloud structure, precipitation forms	1	24	0.60	Sequential cloud images	5*, 6, 7, 8
	3	5	15	0.40	Atmospheric heat balance	1	24	0.60	Sequential cloud images	5, 6, 7, 8
	5	5	14	0.70	Cloud structure, precipitation forms	1	24	0.60	Sequential cloud images	5, 6, 7, 8
	5	5	15	0.30	Atmospheric heat balance	1	24	0.60	Sequential cloud images	5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parentheses.

6.0 CONCLUSIONS

The outstanding requirements for knowledge of the planets concern surface composition and topography, atmospheric composition and circulation, and interior structure. Although remote sensors can support all of these requirements, their greatest contribution is to atmospheric studies, especially at the outer planets.

The observation requirements tabulated in Volume 4 are distributed among planets, wavelength regions, and kind of measurement, as shown in Tables 13 and 14. Requirements involving several spectral regions are listed under each region in Table 14.

Table 13. Distribution of Observation Requirements by Planet

Planet	ORDS
Mercury	24
Venus	31
Mars	24
Jupiter	69
Saturn	71
Uranus	65
Neptune	65

The greater number of observation requirements defined for the outer planets reflects the inclusion of imagery. Most imaging observations defined for Saturn, Uranus, and Neptune are also required for Jupiter and are defined for that planet although such definition is nominally outside the scope of the study. The most frequently represented kinds of measurement are passive imagery, radiometry, and spectrometry. The infrared and visible spectral regions account for more requirements than do other regions. It must not be inferred that the other observation types and spectral regions are less important. Indeed, visible imagery and infrared radiometry and spectrometry are the most important types. However, a balanced and comprehensive planetary exploration program should include all types, for each type makes unique contributions to knowledge of planetary environments and properties.

Table 14. Distribution of Observation Requirements by Spectral Region and Kind of Measurement

Wavelength Region	Passive Imagery	Radiometry and Photometry	Spectrometry	Polarimetry	Radar and Laser	Occultation	Particles and Fields	Total
Radio (>1 cm)	0	4	0	1	5	4	0	14
Microwave (100μ to 1 cm)	2	7	4	2	0	0	0	15
Infrared (0.7 to 100μ)	2	9	10	0	2	1	0	24
Visible (0.4 to 0.7μ)	9	3	3	1	0	2	0	18
Ultraviolet (0.1 to 0.4μ)	0	3	10	0	0	0	0	11
X-ray, γ-ray (<0.01μ)	0	0	2	0	0	0	0	2
Not applicable	0	0	0	0	0	0	6	6
Total	13	26	29	4	7	7	6	92

REFERENCES

1. Klopp, D. Orbital Imagery for Planetary Exploration. IIT Research Institute, Chicago (January 1970).

2. Space Research: Directions for the Future. National Academy of Sciences, Publication 1403, Washington (1965).

3. Planetary Exploration, 1968-1975. National Academy of Sciences, Washington (1968).

4. The Outer Solar System. National Academy of Sciences, Washington (1969).

5. Manned Planetary Flyby Missions Based on Saturn/Apollo Systems. Space Division, North American Rockwell Corporation, SID 67-549 (August 1967). (Contract NAS8-18025)

6. Service Module Planetary Spacecraft. Space Division, North American Rockwell Corporation, SD 68-6 (February 1968).

7. Outer Planet Exploration Mission Study. Space Division, North American Rockwell Corporation, SD 70-20 (January 1970). (Part B of Contract NAS8-24975)

8. Goody, R. "The Atmospheres of the Major Planets," Journal of the Atmospheric Sciences, No. 26 (1969), p. 997.

9. Hunten, D.M. "The Upper Atmosphere of Jupiter," Journal of the Atmospheric Sciences, No. 26 (1969), p. 826.

10. Trafton, L.M. and G. Munch. "The Structure of the Atmospheres of the Major Planets," Journal of the Atmospheric Sciences, No. 26 (1969), p. 813.

11. Mintz, Y. "The General Circulation of Planetary Atmospheres," Proceedings of the Lunar and Planetary Exploration Colloquium, Vol. III, No. 1, North American Aviation, Inc., Los Angeles (1962).

12. Hide, R. "Dynamics of the Atmospheres of the Major Planets With an Appendix on the Viscous Boundary Layer at the Rigid Bounding Surface of an Electrically Conducting Rotating Fluid in the Presence of a Magnetic Field," Journal of the Atmospheric Sciences, No. 26 (1969), p. 841.

13. Stone, P., et al. "Preliminary Results of Experiments With Symmetric Baroclinic Instabilities," Journal of the Atmospheric Sciences, No. 26 (1969), p. 991.

14. U.S. Standard Atmosphere Supplements, 1966. ESSA-NASA-USAF, U.S. Government Printing Office, Washington (1966).

15. Smith, R.E., and D.K. Weidner (editors). Space Environment Criteria Guidelines for Use in Space Vehicle Development (1968 Revision). NASA TM X-53798 (31 October 1968).

16. Carpenter, J., et al. "Lunar Surface Exploration by Satellite," American Science and Engineering, Inc., ASE-1919 (June 1968).

17. Kliore, A., et al. "Atmosphere and Ionosphere of Venus From the Mariner V S-Band Radio Occultation Measurement," Science No. 158 (1967), p. 1683.

18. Love, A.W. Satellite Sounding of the Martian Atmosphere, Autonetics Division, North American Rockwell Corporation, T8-97/060 (21 February 1968).

19. A Study of Scientific Mission Support of a Lunar Exploration System for Apollo, Vol. III, Scientific Studies, Space Division, North American Rockwell Corporation, SID 65-289-3 (16 June 1965).

20. Guérin, P. Comptes Rendus (to be published).

21. Kuiper, G.P. Press Release (29 November 1969).

22. Ozier, I., W. Ho, and G. Birnbaum. "The Pure Rotational Spectrum and Electric Dipole Moment of CH_3D," Journal of Chemistry and Physics, No. 51 (1969), p. 4873.

APPENDIX A. DETERMINATION OF ATMOSPHERIC PHYSICAL PROPERTIES FROM SPECTRAL DATA*

For the present purpose, only the simplest model is considered whereby it is assumed that the incident solar energy is reflected by a well-defined reflecting layer and the lines are formed in the absence of scattering above this layer. Although the model is admittedly crude, the simple expressions which result do serve to give a qualitative description as to the manner in which the physical properties of the atmosphere are related to the properties of the measured spectra. These relationships should not be very much different from the results of more complicated analysis. They are equally applicable for the case where the absorption spectrum is obtained by observing the Sun through the planetary atmosphere in an occultation-type experiment.

PRESSURE

The integrated absorption S(J) for an isolated line corresponding to a rotational transition (either pure rotational or rotational-vibrational) from J to J+1 is defined by,

$$S(J) = \int_0^\infty \alpha_J(\nu) d\nu ,$$

where $\alpha_J(\nu)$ is the absorption coefficient per unit length for this transition which appears in Lambert's Law:

$$I/I_o = e^{-\alpha_J(\nu)L} .$$

Here I/I_o is the fractional transmission through the absorber of length L.

For a collision-broadened line (such as is considered here), the absorption coefficient $\alpha_J(\nu)$ can be approximated by the Lorentz expression,

*By Dr. W. W. Ho, NR Science Center.

$$\alpha_J(\nu) = \frac{S(J)}{\pi} \frac{\gamma(J)}{[\nu - \nu_J]^2 + \gamma^2(J)}$$

where $\gamma(J)$ is the half-width at half maximum of the line, S(J) is proportional to the density of the absorbing molecule ρ_α, and $\gamma(J)$ is proportional to the total density of the atmosphere, ρ_T,

$$S(J) = \rho_a S_o(J);$$

$$\gamma(J) = \rho_T \gamma_o(J).$$

Here $S_o(J)$ and $\gamma_o(J)$ are the values of S(J) and $\gamma(J)$, respectively, at a density of one atmosphere, which are measured in the laboratory.

For such an isolated line, it is possible to measure both S(J) and $\gamma(J)$ in a straightforward manner provided the resolution of the spectrometer $\Delta\nu$, is such that

$$\Delta\nu / \ (J) << 1.$$

The line half-width γ is related to the density and temperature by the relationship,

$$\gamma = \gamma_o \left\{\frac{\rho_T}{\rho_o}\right\} \left\{\frac{T_o}{T}\right\}^{1/2} .$$

Since γ_o at ρ_o, and T_o (usually chosen at standard conditions of 273 K and 1 atm.) is known, the mean density of the atmosphere at which the line is formed in the atmosphere is then simply given by

$$\rho_T = \frac{\gamma}{\gamma_o} \left\{\frac{T}{T_o}\right\}^{1/2} \quad \text{(atm.)},$$

where T is the mean temperature of the atmosphere at the altitude where the line is formed.

Since the temperature can be determined independently by either infrared emission measurements or by measuring the variation of S(J) with J, and since usually the variation of T with altitude is gradual, i.e.,

$$\frac{T(h) - T(h + \ell)}{T} << 1$$

where ℓ is the mean free path for the radiation at ν, the accuracy in the determination of the mean density of the atmosphere is just proportional to the accuracy with which γ is measured, i.e.,

$$\frac{\Delta \rho_T}{\rho_T} \quad \frac{\Delta \gamma}{\gamma}.$$

It is immediately apparent that, if $\Delta \nu / \gamma(J) \geq 1$, then no information can be obtained regarding the atmospheric density.

TEMPERATURE

The rotational temperature may be determined by the ordinary Boltzmann equation method by noticing that S(J) is proportional to the population in the J^{th} state, N(J). If the temperature variation in the path length is not severe, then the rotational temperature is a good approximation of the physical temperature at the level where the lines are formed. For this case,

$$\log S(J) = A(J) - \frac{B(J)}{T_{rot}}$$

where A(J) and B(J) are constants for a given J.

If the integrated intensity S(J) is measured for several lines of different J states, then T_{rot} can be determined. The accuracy with which T_{rot} is determined is given by:

$$\frac{\Delta S(J)}{S(J)} = \frac{B(J)}{T} \left| \frac{\Delta T}{T} \right| .$$

B(J)/T can, for some cases, be larger than unity and therefore S(J) must be accurately measured in order to give a T_{rot} accurately to a few percent or so. In this instance, the resolution of the spectrometer need not necessarily be better than the linewidth, i.e., it is possible to work in the limit where

$$\Delta \nu / \ (J) \geq 1.$$

In this limit, slit function effects enter which make the measured integrated intensity smaller than the actual intensity S(J). However, techniques (commonly referred to as "curve of growth" methods), exist for correcting for these effects, so that an accurate value of S(J) can still be determined. More exact analysis for the case of a scattering atmosphere results only in changing the constants A and B.

ABUNDANCE

The equivalent path length of the molecule giving rise to the observed spectral line may be estimated roughly by assuming the simple reflecting-layer model for the atmosphere. The equivalent path length is then given by,

$$P_a L = \frac{S(J)}{S_o(J)} L \text{ (meter-atm.)}$$

where L is double path length above the reflecting layer and $S_o(J)$ is measured in the laboratory at the mean temperature T_{rot} of the atmosphere.

The mixing ratio for the absorbing molecule is then given by

$$\rho_a / \rho_T = \frac{S(J)}{S_o(J)} \frac{\gamma_o(J)}{\gamma(J)} .$$

The fractional changes are then correspondingly

$$\frac{\Delta(\rho_a L)}{\rho_a L} \propto \frac{\Delta S(J)}{S(J)}$$

and

$$\frac{\Delta(\rho_a/\rho_T)}{(\rho_a/\rho_T)} \propto \frac{\Delta\rho(J)}{S(J)} + \frac{\Delta\gamma(J)}{\gamma(J)} .$$

Again it is apparent that the equivalent path length may be deduced from spectra taken with a spectrometer of inferior resolution whereas the mixing ratio requires that the spectral resolution be much better than the widths of the individual lines.

APPENDIX B. CONSULTANTS' REPORTS

This appendix contains the reports of consultant scientists retained by North American Rockwell (NR) to support the Remote Sensor study. The consultants are:

Prof. Gerard de Vaucouleurs, Department of Astronomy, University of Texas, Austin, Texas

Prof. Reginald E. Newell, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Massachusetts

The reports presented here are unedited except for format.

Page B-2 Missing in Original Document

A SURVEY OF SCIENTIFIC OBJECTIVES, OBSERVABLES, AND EXPERIMENTS FOR FLYBY MISSIONS TO THE OUTER PLANETS

G. de Vaucouleurs

1.0 INTRODUCTION

This document is a preliminary survey of the scientific objectives, observations, requirements, and measurement requirements to be considered in planning remote sensor observations of the outer planets during flyby missions to Saturn, Uranus, and Neptune. Both imaging and nonimaging sensors will be considered. In the first part, a survey of scientific problems and objectives applicable to all the outer planets will establish a framework of the discussion; next, a brief survey of available or potential techniques of observation will define the tools which, in principle, could be operated from a spacecraft (with some extrapolation of current technology); and finally, objectives, observables, and instruments will be compared in terms of actual experiments. In a second part, a special discussion of each planet with appropriate scaling factors will serve to define the parameters of detailed feasibility studies.

2.0 SCIENTIFIC OBJECTIVES

Information on the major planets can be organized under three main topics: general or global properties, atmospheric structure and properties, and internal structure.

2.1 GLOBAL PROPERTIES

Global properties include the gross features of the planet and its relations to the environment—its mass, diameter, density, magnetic, electric, and gravitational fields. Of particular interest for the outer planets are the diameters and ellipticities which are still poorly known (especially in the case of Uranus), and this, in turn, leaves much uncertainty on the mean density. In the special case of Saturn, the thickness and particle density of the ring system, the absence or presence of suspected minor divisions, and their possible relations to satellite orbital periods are still essentially unknown or in grave doubt. There is a general agreement that the outer planets fall into two groups: Jupiter and Saturn on the one hand, Uranus and Neptune on the other. Yet the radio-emission properties of Saturn are more akin to Uranus and Neptune than Jupiter. Because of the greater distance, very little is known of the radio properties of Uranus and Neptune. Among the basic objectives of flyby missions to the outer planets should be included studies at close range of the thermal and nonthermal (if any) radio emissions, of the magnetosphere and trapped particles belts (if any), of its interaction with the solar wind, a search for a possible tail to the magnetosphere, and perhaps use of the latter as a probe to estimate the relative importances of the solar and stellar (galactic) winds in these outer regions of the solar system.

2.2 ATMOSPHERIC PROPERTIES

Atmospheric properties constitute the major observables of the outer planets. The following seem to be the most important or most directly accessible to remote sensing.

2.2.1 Chemical and Isotopic Composition

The abundances of hydrogen and helium and H/He ratio are of paramount importance because of their cosmogonic and possibly cosmologic implications;

next in importance are the abundances of carbon and heavier elements at least up to potassium and argon; next in line are the isotopic ratios, especially $^{13}C/^{12}C$, $^{2}D/^{1}H$, $^{3}He/^{4}He$, and $^{36}A/^{40}A$. All these are potential clues to the origin and evolution of the galaxy and the solar system.

2.2.2 Vertical Structure

Knowledge on depth, scale height, temperature and density distributions, and variations of composition in the atmospheres of the giant planets is still largely hypothetical. Observations of stellar occultations can give information on exospheric temperatures, escape rates, and (through the scale height variations) on the H/He ratio. Observations of radio beacon occultations could give information on molecular and electronic densities over a larger pressure range (< 1 atm). Airglow observations, i.e., of night-side optical emissions, such as the He λ584 resonance line, could also contribute information on composition and density.

2.2.3 Composition of Clouds and Organic Compounds

The presence of methane and ammonia in the atmospheres of the outer planets suggests the possibility of more complex organic compounds formation which may have a bearing on the origin of life in the primitive atmosphere of the earth. A number of relevant or related questions are: What is the chemical composition of the particles in the clouds? Are they colored by organic compounds? Are the color changes related to variable phase equilibria governed by changes in temperature or density (due to possible vertical oscillations)? Are electrical discharges present? What chemical reactions take place in the upper atmosphere above the clouds? What hydrides, such as OH, H_2O, H_2S, are present and what role do they play in the organic chemistry of the clouds and atmosphere?

2.2.4 Kinetic and Dynamics

The large-scale circulation of the atmosphere of Jupiter as evidenced by cloud motions has been studied for many decades, but little is known of the kinetics of the atmospheres of the outer planets. The belt structure is weak and definite spots are rare on Saturn. The existence of a belt structure on Uranus, and especially on Neptune, is still in doubt; direct imaging observations at close range are needed to solve this fundamental question. Horizontal and vertical temperature gradients must be determined before a realistic model of the dynamics and "meteorology" of these atmospheres can be even formulated. In particular, it is of great importance to determine whether, as on Jupiter and possibly Saturn, internal energy sources contribute significantly to the radiation balance of the outer planets. If definite

cloud structure is weak or absent even at close range, spectroscopic determinations of horizontal velocity gradients (as well as improved data on the general rotation of the planet) will be important for Uranus and Neptune.

2.2.5 Scattering Properties

Detailed and even integral scattering properties of the outer planets are still very poorly known because the phase angle never exceeds a few degrees (6 degrees for Saturn, 1.5 degrees for Neptune) and consequently the phase functions and integrals cannot be observed and computed. It follows that the spherical albedos are unknown, except in unverified model atmosphere calculations. This fact and the incompleteness of the spectral energy curve combine to leave the radiometric albedo almost indeterminate within wide limits (at least 50-percent uncertainty). In addition to multicolor phase curves over a large range of phase angles, detailed observations of the monochromatic limb-darkening laws, both along the equator and the meridian, are needed to build and check realistic models of atmospheric structure and scattering properties of the atmospheres of the outer planets. In the case of Saturn, special studies of the spectral reflectivity and phase function, as well as opacity of the ring system, are also needed.

2.3 INTERNAL STRUCTURE

Models of the interiors of the outer planets range over a wide spectrum, some with hot, semi-stellar interiors, some with cold, icy cores; some problems that might be solved by remote sensor observations from flybys have a bearing on the internal constitution problem

2.3.1 Magnetic Fields

The presence of a strong magnetic field, such as the one indicated by radio observations of Jupiter, may give information on the presence or absence of an electrically conducting core or shells (fluid layers) in the outer planets. Since no definite observation exists of nonthermal emission from these planets, detection should be attempted during near encounters.

2.3.2 Thermal Emission

The spectral energy distribution of thermal radiation from the planet in the radio and infrared ranges may give information on temperature gradients below the visible cloud tops and help detect internal heat sources, such as are believed to account for the excess radiation temperatures of Jupiter and possibly Saturn over that which balances the solar flux. Detailed thermal mapping will also help understand radiation exchanges in the atmosphere below the cloud tops. The chemical composition of the lower levels of the atmosphere may be reflected in details of the infrared thermal emission spectrum and, in particular, bands of methane and ammonia. Possibly other compounds may be observable. Similarly, in the microwave spectrum observation of the 1.25-cm line of NH_3 and of the 1.35-cm line of H_2O should give information on atmospheric composition and pressure below the visible clouds.

2.3.3 Mass Concentration

Detailed analysis of the gravitational deflection of the orbital path of a probe in close encounter may give information of the degree of mass concentration and dynamical ellipticity of the planet, and serve to narrow down the range of acceptable models of internal structure.

3.0 METHODS OF OBSERVATION AND OBSERVABLES

A large array of tools and methods of observation is available which bear on one or several of the scientific objectives listed in Section 2.0.

3.1 OPTICAL IMAGING

Optical systems of different apertures and focal lengths, associated to Vidicon-type image sensors, are available to provide direct imagery on a much greater scale and resolution than is presently provided by ground-based telescopes or is currently envisaged for near-earth orbital observatories of the next 20 years. For example, practical resolution of one arc-sec (in the sense of modulation transfer function = 1/2) is seldom exceeded on earth-bound telescopic photographs of the outer planets which, because of the low illumination levels, require long exposures. One arc-sec corresponds to the following linear resolutions at mean opposition:

Saturn, 6,000 km; Uranus, 12,400 km; Neptune, 20,000 km.

Marginal detection is possible on rare photographs down to perhaps 1/4 arc-sec. For comparison, a Mariner-type Vidicon system placed at the focus of a 50-mm lens and a 500-mm Cassegrain system has a theoretical resolution limit (R. L.) (one line pair) of approximately 20 inches and 2 inches, respectively, giving the following linear resolutions at several ranges:

Range	(km)	10^6	10^5	10^4	10^3
50 mm f. l.	R. L.	100	10	1	0.1
500 mm f. l.	R. L.	10	1	0.1	0.01

These figures are optimum values for unit-contrast, simple targets and do not allow for possible image motion (blurring); on low-contrast targets such as the cloud structure of the outer planets, resolution limits may be almost an order-of-magnitude poorer. Also, the shortest distance may not be realistic. Even with these restrictions, the resolution gains over ground-based photography are in the range 10 to 10^3 for Saturn and up to 10^2 to 10^4 for Neptune.

From such direct images, and provided uncalibrated distortions of the electronic readout system do not exceed the resolution limit, diameters and optical ellipticities of the three outer planets could be derived to a degree of accuracy far in excess of present ground-based data which is of order 0.1 to 0.2 arc-sec of the mean opposition apparent diameter, or about 1 percent for Saturn, and perhaps 5 percent for Uranus and Neptune (the diameter of Neptune is now known more precisely from a recent stellar occultation). Direct images in several colors will be needed to decide whether the edge of the planet is defined by a definite cloud surface or by a critical optical depth in a molecular or particle atmosphere.

Direct images of large-enough scale over periods of time greater than one rotation period (10 to 16 hours) may provide enough detailed information on motions of discrete cloud formations to establish much more precisely the rotation periods of Uranus and Neptune and differential rotation as a function of latitude on Saturn (and possibly on the other two planets).

It is known that differential rotation follows different laws on Jupiter and Saturn, represented by two discrete periods (Systems I and II) of about 9 h 50 m and 9 h 55 m on Jupiter, and by a more continuous transition from 10 h 14 m at the equator to 10 h 38 m at latitudes ± 45 degrees on Saturn—if the few definite spots observed in the past century are representative. This difference needs to be confirmed and similar studies of the two outer planets are needed. All this could be done by simple optical imaging, which deserves high priority on the list of flyby experiments. Exposure times may be considered, using for illustration the Vidicon systems and exposure times used in the Mariner 1969 and 1971 missions to Mars:

Planet	Mars	Saturn	Uranus	Neptune
Visual surface brightness in mag/(arc-sec)^2 at mean opposition	4.5	6.9	8.2	9.6
Relative exposures	1.0	9	30	110
Typical exposure (unfiltered)	0.003s	0.03s	0.1s	0.3s

Outside the normal visual (yellow-green) visual range, details of the respective spectral reflectivity curves should be considered (see Section 6.0).

3.2 PHOTOMETRY

Photometry should be one of the most important tools in an investigation of the outer planets by remote sensors because of the phase angle and

resolution limitations of ground-based observations. We need to determine the normalized (relative) integral intensity of the planet as a function of phase angle from 0 degrees (opposition, full phase) to as close to 180 degrees (sun occultation) as possible and over a wavelength range as large as possible, at least from 0.2 to 5 microns. A standard photoelectric photometer with a choice of photodetectors and filters at the focus of a small reflector (4- to 8-inch aperture) should be sufficient to make useful observations within 10^8 km from each of the outer planets. The filter bandwidth can be fairly large, about 0.1 of the central wavelength chosen outside the main absorption bands of methane and ammonia. The scaling factors can be derived from the visual magnitudes of the three planets at mean opposition V_o or from the corresponding value V_1 (0) at unit distance from the sun and earth:

	Saturn*	Uranus	Neptune
V_o	+0.67	+5.52	+7.82
V_1 (0)	-8.88	-7.19	-6.89

*With ring edge on

It will be especially important to determine directly the phase function F(i) and phase integral q, which are still unknown because of phase angle limitations; according to theoretical calculations q may range from 1.25 for Rayleigh scattering, to 1.45 for isotropic scattering, to 1.77 for some models (Chandrasekhar, Horak) of anisotropic scattering. This uncertainty is reflected in full in the value of the spherical albedo A = pq, where p, the geometric albedo, is the only factor known from ground-based observations (it follows from V_o) (see Section 6.0).

Spectrophotometry at medium resolution, say 0.01 of the bandwidth, will be needed over the largest practicable spectral range not subject to thermal emission, say 1216 A to 10 microns, to derive more precisely the spectral albedo curve and compute the total radiometric albedo A^* for solar radiation. If the wavelength dependence of the phase integral is well defined by the broadband photometry (see above), spectral observations may be limited to the optimum combination of phase and range of the planet to maximize the energy available. The inverse square of the range (as long as the disk of the planet does not exceed the field-of-view of the photometer) is the dominant factor because the phase coefficient at small phase angles is unlikely to exceed 0.01 magnitude per degree, or a 10-percent correction at 10 degrees phase angle; at larger phase angles an approximate estimate may be made from the Lambert phase function, which gives Q = 1.50, near the middle of the range of various theoretical estimates noted above.

At shorter ranges, detailed photometry and spectrophotometry could be obtained with essentially the same photometric sensors, if slewing capability is provided for scanning along the equatorial and polar diameters of the planets. This also would be useful as a calibration check on the photometric response of the direct imaging sensors and to extend knowledge of limb-darkening functions to a greater range of wavelengths. Of particular importance will be scans in narrow wavelength bands within the absorption bands of methane and ammonia. Only very crude preliminary information is available on the limb-darkening curves of Saturn, and none at all for Uranus and Neptune. From an analysis of minor effects in the integral photometry of Uranus, there is preliminary evidence that the coefficients of the limb-darkening law are different along the equator and a meridian; direct verification is important (see Section 6.0).

3.3 POLARIMETRY

Light reflected by the planets is partially polarized in a manner characteristic of the nature and structure of the scattering particles. The degree of polarization is generally small, often less than 10 percent, but it could be large under some circumstances. For instance, a Rayleigh scattering atmosphere observed at right angles to the direction of incidence may have close to 100-percent polarization. Because of the severe restriction of phase angles observable from earth and the faintness of the light of the two outer planets, this technique has not yet delivered its potential. The situation will be quite different from spacecraft if a large range of phase angles is observable at distances small enough to give good resolution of the disk. Even at large ranges, a fair degree of polarization of the total light of Uranus and Neptune, possibly 30 to 50 percent, might be observed if, as has been suspected, Rayleigh scattering plays a major role in explaining the blue-green colors of these planets (in addition to selective absorption by molecular bands). More important will be studies of the detailed distribution of polarization over the disks, and in particular center-to-limb darkening curves in the two main directions of the electric vector (along the radius and perpendicular to it).

This information at several wavelengths selected by broadband filters is essential for a detailed verification of theories of atmospheric scattering and to differentiate between molecular and particle scattering as the main contributor to the diffuse reflection of sunlight by the outer planets. It is expected that the relative contributions will vary with latitude, in particular in the polar regions, where preliminary information on Jupiter and possibly Saturn suggests that pure molecular scattering may be dominant. The instrumentation needed for this type of study is essentially the same as for direct imaging and photometry, with the addition of suitable polarizing filters capable

of four, or better, six, fixed, known orientations. High photometric precision is necessary for a useful interpretation, about 0.1 or 0.2 percent with the photoelectric photometers, and 0.5 to 1 percent with the imaging devices whose lower intrinsic precision will be compensated by the greater number of image picture elements resolved. High angular resolution may not be essential; something like 100 x 100 resolved picture cells in the planetary disks should be adequate for the testing of theoretical models; at least four color bands are necessary ranging from near ultraviolet to near infrared (polarization of planets and natural substances is often near a maximum in the green region). As a minimum, two colors (blue and red) and 10 x 10 resolution elements should give some useful information.

3.4 SPECTROSCOPY

Ground-based, high-resolution spectroscopy of the integrated light of the outer planets with large coudé spectrographs and Fourier transform spectrometers is expected to be a major item of NASA-sponsored programs in support of space missions during the next 15 years. There is little expectation that instrumentation comparable in weight, size, and complexity to these large and cumbersome systems can be flown by spacecraft during the same time span. It follows that the emphasis of space missions should be to explore spectral regions inaccessible from the ground because of absorption by the earth atmosphere, and to take full advantage of the close range at encounter for studies which require a higher angular resolution of the planetary disk than is possible from earth. Very little resolution is available on Saturn, and practically none on Uranus and Neptune where the mere detection of inclined lines to estimate the rotation period was a tour-de-force that has not been successfully repeated in 40 years.

Typical performance figures of present or contemplated ground-based spectrographs applicable to visible or near-infrared studies of the outer planets are spectral resolutions of the order of 10^5 (about 0.1 cm^{-1}) in the 0.3 to 1.0 micron range, and of the order of 10^4 (about 1 cm^{-1}) in the 1 to 3 micron range, with exposure times in the 10 to 100 hours range with assistance of image converters in the infrared. Angular resolution could, in principle, be as small as 2 arc-sec (or 10 x 10 elements in the disk of Saturn, 2 x 2 for Uranus and Neptune) if all systems and the atmosphere worked at their theoretical best. In practice, it is doubtful that a resolution better than 3 or 4 arc-sec will be achieved with the long exposures required, leaving very little room for detailed studies of Saturn and none at all for Uranus and Neptune.

With these factors in mind, the following projects seem to deserve first consideration for spectroscopic observations from flybys: ultraviolet scanning spectrometry at medium resolution, about 1 cm^{-1} (10^3 to 10^4), of the spectral range 0.1 to 0.3 micron, to extend the absorption-reflection spectrum of the disk and, at close range, to search for characteristic fluorescence of the upper atmosphere on the dark side. Of special interest are the resonance lines of helium (584 A), hydrogen (1216 A), and other light elements; a search for resonance lines of lowest order of ionized molecules, such as $[N_2^+]$ (3914 A), might be warranted. Since many other molecules and radicals might be optically active, a complete exploratory program rather than selective search at a few wavelengths appears advisable.

An infrared scanning interferometer for Fourier transform spectrometry of the 1 to 20-micron range at the highest practical resolution (0.1 cm^{-1}) is required to resolve the rotational structure of the NH_3 and CH_4 bands, with emphasis on the spectral regions blocked off by telluric absorptions in ground-based observations. At short distances where angular resolution of 10 (minimum) to 100 resolution elements will be available in the disk of each planet, it will be of great interest to study the variations of the band strengths as a function of longitude and latitude, to derive seasonal as well as diurnal effects on the solid-gas equilibrium of the molecules, and possible effects of variable optical depth through the atmosphere (e.g., due to variation of cloud level with latitude). If the rotational structure can be resolved, fine studies of the rotational temperature of the bands as a function of optical depth will become possible. The methane bands at λ 8873 and 9706 A should be especially useful for such studies.

In addition to molecules known to be present on the outer planets, a search should be made for other compounds which chemical theory suggests as possibly present; among them, ordinary water may be locked up with NH_3 crystals in the clouds as hydrated forms $NH_3.H_2O$ and $2NH_3.H_2O$. Similarly, H_2S may be depleted by formation of solid ammonium hydrosulfide (NH_4SH) in clouds at higher elevation than the NH_3 hydrated clouds. Other compounds that have been discussed as possible present in the atmospheres of the outer planets include SiH_4, SiO, and the noble gases.

In the ultraviolet, it has been suggested that a search be made for the displaced Raman line of Lyman alpha scattered by molecular hydrogen; the expected wavelength is 1280 A and it could be sought in the upper atmosphere projected against the dark side of the planet near the terminator. Extreme precautions against scattered light from the illuminated disk and long integration times will be required.

3.5 INFRARED RADIOMETRY

Thermal detectors associated with broadband filters and/or low-resolution spectrometers should be used to derive the energy distribution of

the thermal emission of the planets in the 5 to 25-micron range. With radiative equilibrium temperatures in the 50° K to 150° K interval, the expected maxima of the spectral energy curves are in the 20 to 60-micron range; however, departures from a simple black body curve at a single effective temperature may be observed if, at least in the case of Saturn, internal heat sources play a significant role in the heat balance of the planet. Only mean temperatures of the entire disk are available for Saturn at 10 and 20 microns, marginal observations for Uranus, and none for Neptune. Detailed observations of the distribution of thermal emission over the disk of Saturn (including the dark side) with a resolution of at least 10 x 10 elements (20 x 20 may be needed to clearly resolve the belt structure) are needed, as well as total radiation spectra of Uranus and Neptune to supplement the temperature indications from spectroscopic and microwave studies (Sections 3.4 and 3.6).

Uranus presents a special problem because of the high inclination of the rotation axis, resulting in the planet being illuminated by the sun either pole-on or equator-on four times per revolution period. If the sun is the only heat source, effective temperatures are expected to vary between 50° K in the first presentation and 73° K in the second, subject to present uncertainties in the radiometric albedo.

Attempts to detect thermal emission from the dark side of Uranus and Neptune also would be of value to check on possible internal heat sources. If at the closest range, thermal maps of the two outer planets can be obtained at one of two wavelengths in the expected range of maximum emission (40 to 60 microns), a resolution of 10 x 10 elements should be sufficient to attempt correlation with possible belt structures in the optical picture.

Thermal maps of the ring of Saturn with about 100 resolution elements in the width of the ring should be a special value to assist in estimating the effective cross-section, as well as the effective temperature of different parts of the ring system. A direct comparison of the thermal emission spectra of the ring and the globe will also facilitate the search for weak molecular absorption bands in the far infrared spectrum of the globe.

3.6 MICROWAVE RADIOMETRY

The millimeter and centimeter waves cover a spectral region of great importance for the thermal balance of cold planets and include some discrete absorption lines of major significance. Microwave observations from flybys, if possible with some angular resolution (10 x 10 on Saturn, 5 x 5 on Uranus and Neptune), deserve a high priority. Continuum emission near 1, 3, 10, 30, and 100 mm wavelengths should be sufficient to define the thermal spectrum and effective temperature. Of special interest are observations at 12.5 and 13.5 millimeters, corresponding to the absorption lines of NH_3 and H_2O; positive detection and study of the center-to-limb and center-to-pole variations should greatly assist theories of the cloud and atmospheric structures. Such observation is likely to be simpler for Saturn if there is an internal heat source providing a stronger background emission than in the case of pure solar heating. Again, if internal heat is present, microwave emission might be detectable on the dark side of the planet and study of the day-night cycle of emission at several wavelengths will help separate the contributions of the internal and external heat sources. If radio observations at longer wavelengths (Section 3.7) confirm the absence of nonthermal emission from Saturn and the two outer planets, the separation of the microwave emission into two components should be definite.

Thermal maps of the ring system of Saturn, with a resolution of at least 10 elements in the width of the ring and at least two wavelengths, would be useful to supplement the infrared radiometry (Section 3.5).

3.7 LONG-WAVE RADIO EMISSION

The strong nonthermal emission of metric and decametric waves by Jupiter has not yet been detected from the other outer planets. Its absence is particularly surprising in the case of Saturn because of its otherwise close similarity with Jupiter. Two sources are identified on Jupiter: the continuous emission from the radiation belt of particles trapped in a strong magnetic field, and the discrete deep-seated sources of the noise bursts associated with the quasi-solid body System III rotation period of the magnetic field. It is possible that much weaker emissions of this type might be detected at closer range, at least from Saturn. Failure to detect such emission at decimetric and metric wavelengths would indicate that the planet lacks a radiation belt and perhaps a magnetic field of significant strength, or alternatively, that the ring system effectivly sweeps clean the potential radiation belt region. Less likely is the hypothesis that the solar wind becomes insignificant at the greater distances from the sun.

Likewise, no long-wave (i.e., longer than 20 cm) emission has been detected from Uranus and Neptune; a search for such emissions at close range is clearly needed to help detect nonthermal emission and possible trapped radiation belts.

3.8 RADAR OBSERVATIONS AND RADIO OCCULTATIONS

S-band observations of the occultation of a transmitter carried by the probe as it passes behind the planet provide a powerful method of determining electronic and molecular densities in the atmospheres of planets. A solid

or liquid surface or, more generally, a phase change discontinuity could be detected well below the visible clouds by such observations at longer wavelengths penetrating to the lower atmospheric levels. Similar observations could be made with an active radar system on board used at close range to study occultations of the satellites by the planet. (Studies of optical occultations of the satellites and even stars by the planets would give information on the upper atmospheric densities and scale height but might be more difficult to perform at the larger distance range needed to give the optical technique the required leverage.) Of great importance, of course, is the Doppler radar tracking of the probe itself to determine the orbital perturbations due to the planets themselves and, therefore, more precise values for the masses of the outer planets. During the period of closest approach, if the range can be brought down to 10^4 km or so, the quadrupole term in the gravitational field may become measurable and give some indication of the internal structure of the planet and in particular the mass concentration, the basic information for any realistic model of the internal constitution of the outer planets.

4.0 SCIENTIFIC OBJECTIVES, OBSERVABLES, AND REMOTE SENSOR REQUIREMENTS

In this section the scientific objectives are reviewed under major headings. The observable parameters relating to each objective are listed and the remote sensor requirements for the determination of each parameter are indicated. Except for the ring system of Saturn, requirements are qualitatively the same for the three outer planets; differences are mainly quantitative and determined by the scaling factors (Section 5.0).

4.1 SURFACE COMPOSITION

On a planet with a visible solid surface, or if there is a solid or liquid or phase change surface below the cloud decks of the outer planets, the scientific objectives would come under the headings of mean surface density, surface chemical composition, and surface isotopic ratios. Observables having a bearing on these problems are the ultraviolet, visible, infrared reflection spectrum, and the thermal emission spectrum, including its diurnal variations governed (in the absence of internal heat source) by the density, specific heat, and heat conductivity of the surface materials determining the thermal inertia. The radar reflectivity and its variation with wavelength depend on the dielectric constant of the surface materials within a few centimeters from the exposed layer. The principal methods of analysis available using only remote sensors include photometry, in particular detailed photometry with good angular resolution; spectrophotometry; ultraviolet; visible and infrared spectroscopy; and radar reflectivity studies. It is unlikely that any of these tools will have a direct bearing on the problem of the composition of the solid or liquid surfaces of the outer planets which are hidden by clouds at all visible wavelengths, although there is some remote possibility that active radar probing of the atmospheres at the longest practical wavelengths might detect reflection by a solid surface, in particular on Neptune if all atmospheric gases except hydrogen and helium are frozen out.

4.2 GLOBAL STRUCTURE

The scientific questions relating to the basic properties of the globe of a planet include its mass, radius, and oblateness, or more generally geometric shape, which is related to the principal moments of inertia, rotation period, and mass distribution. The morphology and internal structure of the globe is a matter of mainly theoretical interest, but is related to

some observable or derivable quantities such as the harmonics of the gravitation field. The observables having a bearing on the internal and global structure problems include the apparent shape of the visible surface of the planet, the polar and equatorial diameters, the rotation period or periods if differential rotation is present, its mass and the quadrupole term of the gravitation field.

A variety of remote sensor techniques are applicable to one or several of these observables. Direct imaging with geometric calibration of the field distortion and scale properties will yield accurate values of the apparent and, therefore, linear diameters and the polar oblateness if the direction of the pole of rotation is known (e.g., from the known satellite orbits or from the belt structure). Present uncertainties on the diameters of Saturn, Uranus, and Neptune are of the order of 1 percent and 3 to 5 percent; this precision would be easily surpassed by direct imaging with Mariner-type Vidicon systems associated with 50-mm and 500-mm focus optics at all distance ranges less than the following (assuming a measuring uncertainty of ±1 picture element and 100 TV lines per millimeter in round numbers):

Maximum range for 1% accuracy	Saturn	Uranus	Neptune
50 mm f. l. optics	6.10^6	$2.5.10^6$	$2.5.10^6$ km
500 mm f. l. optics	60.10^6	25.10^6	25.10^6 km

In order to achieve significant improvement on ground-based values, distance ranges of the order of one-tenth or less of the above values will be needed. Subject to the sharpness of the edge of the planet, a gain of two orders of magnitude appears possible over current uncertainties on the diameters.

Direct imaging should be supplemented by photometric scans across the disks of the planets, at least along the equator and central meridian, in order to evaluate the significance of limb darkening in diameter measurements and help define more precisely the atmospheric levels which determine the apparent edge of the disk.

The oblateness of the apparent "surface" of the planet derived from direct imaging should be compared to the dynamical oblateness derived from orbital perturbations of the spacecraft (and the natural satellites). In a close encounter, the harmonics of the gravitation field also may be estimated, but orbiters may be needed for a reliable solution.

Greatly improved values of the masses of the outer planets should also result from the Doppler tracking data as the spacecraft comes to the immediate vicinity of each planet. Masses derived from the natural satellites are of limited precision because of scale factor uncertainties in the micrometric measurements of the radii of the orbits of the satellites on ground-based photographs. Direct TV imaging of the planets and their satellites from the spacecraft at ranges of 10^6 to 10^7 km may be of value here too, if the geometric field distortions can be calibrated out precisely.

4.3 GLOBAL ACTIVITY

The scientific objectives under this heading include the dynamics and thermodynamics of the internal and superficial motions, such as flows and convection or large-scale drifts, and heat exchanges, such as occur in volcanos and other types of localized heat or radiation sources in the globe or near its surface (or phase change interface). There is probably little that can be observed by remote sensing, except perhaps the detection and monitoring of fixed sources of radio emission and their rotation period or periods, if such are present as on Jupiter with a deep-seated origin. The instrumentation required is a metric or decametric receiver of sufficient sensitivity and directivity. It is probable, however, that any internal activity observable near the outer planets will really refer to a not-very-deep atmospheric layer below the cloud tops (refer to Section 4.6).

4.4 ATMOSPHERIC COMPOSITION

The major scientific questions under this heading comprise the chemical composition and isotopic abundances of the gas, and the composition of condensates and particules in suspension in the molecular atmosphere. Observables bearing on these subjects include the reflection and absorption spectrum (optical and radio) of the planet, and, in particular, possible night-side emission due to recombination or twilight zone emission due to fluorescence. The fine structure of the rotation-vibration bands in the red and near infrared (including fluorescence emission if detected) is more specifically the observable for isotopic abundances. The particle scattering is most readily detected in the monochromatic phase functions of reflected sunlight observed over a large range of wavelengths and phase angles (especially near 180 degrees); also, special refraction and diffraction effects such as halos, coronas, parhelions ("sun dogs"), etc., could be observed and give additional information on particle diameters, shapes, and possibly composition.

The tools available for remote observation include direct imaging (halos, etc.), ultraviolet, visible and infrared spectroscopy, and spectrophotometry, in particular for the detection of twilight and night-side (airflow) emissions (including a search for H and He resonance lines, Raman-scattered Lyman alpha) and for abundance determinations from absorption

bands. In addition to the CH_4 and NH_3 bands, particular interest attaches to more precise measurements of the pressure-induced dipole and quadrupole lines of molecular hydrogen.

The isotopic composition studies call for high-resolution spectrographs, probably too bulky for spacecraft operation, or Fourier-transform spectrometry. The microwave radiometer is needed to detect possible narrow absorption features of NH_3 and H_2O at 12.5 and 13.5 mm.

The phase function of scattered light can be determined by multicolor photometry and polarimetry with a suitable compact photometer provided with a set of color and polarizing filters (3- or 4-position angles as a minimum). Complete phase curves of total light and polarization curves of the outer planets at 10 to 20 wavelengths covering the range 0.2 to 5 microns should give enough information for a detailed theoretical attack on the difficult problem of multiple scattering in semi-infinite atmospheres. In general, such observations should be made in relatively clear windows between molecular absorption bands, but additional information would be provided by photometry in a few narrow ranges within the principal absorption bands of methane.

4.5 ATMOSPHERIC STRUCTURE

Under this heading come the science objectives covering the average or global vertical structure of the molecular and particle atmosphere, viz., the pressure-density-temperature distributions in the gaseous atmosphere down to the phase change level (or super-critical level as the case may be), the cloud structure, in particular levels and belts locations, and the upper atmosphere problems, including ionized layers and exospheric region. A good many parameters of interest are observable with remote sensors.

The pressure-density-temperature distributions are reflected in the refraction and scattering constants, the scale height and its variation with elevation, and in the line broadening parameters of pressure-sensitive absorption lines and bands. The cloud structure, in particular the presence of bands and polar caps, is directly observable in the optical image and by scanning photometry of the disk; the proportion of polarized light also is an observable indicator, but of rather more difficult interpretation. The ionization and upper atmospheric layers are detectable by the optical emission spectrum of the upper atmosphere, and by the refractivity for radio waves. A powerful method to detect layers of different optical refractivity (and possibly absorption at lower levels) is the photometry of stellar occultations observed at a great distance range from the planet (strong indication of such layers was obtained recently during the occultation of a star by Neptune), but it may be difficult to predict and arrange for such observations from a spacecraft.

The remote sensor requirements applicable include high-resolution spectroscopy of pressure-sensitive bands and lines, in particular the pressure-induced dipole transitions in hydrogen, and intensity distribution of the rotation lines in resolved rotation-vibration bands (possibly also pure rotation bands in the far infrared observable from a spacecraft). Ultraviolet photometry and spectrophotometry are primary tools for the detection of Rayleigh scattering which may be dominant in the polar regions of Saturn and on the two outer planets (confirmation by polarimetry would be essential). If stellar occultations are a practical proposition, observations are best made through a narrowband interference filter centered in one of the strongest lines of the Fraunhofer spectrum, such as H or K, to minimize contamination by sunlight reflected by the planet (the technique applies mainly to early-type stars in which the K line is weak or absent). If the orbit of the spacecraft can be maneuvered out of the plane of the ecliptic, the possibility of arranging an occultation of Alpha Leonis (Regulus) or some other B-type zodiacal star by one or several of the outer planets should be seriously considered to help derive the scale height in the upper atmospheres (around the 10^{-6} atmospheric level, depending on the planet-spacecraft distance). Similarly, observations of the radio occultations of some of the strongest cosmic radio sources, such as Virgo A (M 87), which are not too far from the plane of the ecliptic, should be considered to help derive the electronic density in the uppermost atmospheric levels. At a shorter range, a radio beacon might be released by the spacecraft and its occultation observed. Finally, occultation of the spacecraft radio signals as observed from the Earth will give electronic and total density data in a manner analogous to the Mariner 4, 5, and 6 occultations by Mars (S-band occultation).

Ultraviolet scanning spectroscopy of the dark side and of the atmospheric twilight fringe with angular resolution of the order of 0.1 percent of the disk apparent diameter, but modest spectral resolution (1 to 10 cm^{-1}) and long-enough integration times (possibly in the 1-min to 1-hr range) should be attempted to search for possible fluorescence and recombination lines of hydrogen (Lyman alpha and H-alpha, possibly the Raman displaced line of L-alpha) and Helium (resonance triplet at 522, 537, and 584 A) in particular. The complex chemistry of the atmospheres of the outer planets may lead to a correspondingly complex molecular spectrum of the night "airglow" similar to, but richer, than the earth's. Here, the possibility of detecting strong resonance lines of relatively rare atomic species, such as sodium and potassium, should not be overlooked.

The cloud structure will be best observed with the television camera and a set of suitable filters, some centered in the clear atmospheric windows, but also some centered in the stronger bands of methane (and ammonia for Saturn only). Infrared and possibly radar scanning of the disks at several frequencies, mainly along the meridians, should give additional information on the belt structure. Of special interest is a search for a belt structure on

Neptune which has been suspected by early observers, but was not confirmed by more modern and presumably more reliable observations.

4.6 ATMOSPHERIC ACTIVITY

The scientific problems under this heading include the large-scale circulation of the atmosphere; the dynamics of cloud condensation, evaporation, and motions; and the role of the atmosphere in the energy exchanges and total heat balance of the planet. Of special interest will be the similarities and differences between the violent activity of Jupiter, the more sluggish activity of Saturn, and the as yet unknown activities of Uranus and Neptune. Special problems such as the Red Spot on Jupiter may or may not arise, but the occasional eruptions of temporary white spots on Saturn are probably related phenomena. Whether such effects also occur on the two outer planets can only be answered by observations at close range.

The observable effects or parameters bearing on these questions include direct imagery - in particular time-lapse studies - and high-resolution spectroscopy to determine rotation velocities and departures from a smooth laminar flow. Of special interest is the latitude dependence of the average atmospheric rotation velocity, i.e., the differential rotation velocities, including special studies of the velocities indicated by the reflected solar lines on the one hand and the intrinsic absorption lines of the atmosphere on the other. Ground-based data are conflicting on the reality of reported systematic differences between the two sets of lines. Also, lines formed at different depths may give different velocities.

Bearing on the problem of heat balance and exchanges are the energy distribution in the thermal emission spectrum (radio and infrared) of the disk as a whole, but more significantly of different parts of the disk as a function of longitude and latitude. Fine studies of the rotation structure of vibration-rotation bands (mainly methane and ammonia) with angular resolution of one-tenth of the disk diameter or better, and limb-darkening curves along the equator and meridians with similar resolution, will also contribute information on this problem of the heat balance.

The remote sensors applicable to such studies include the television system for studies of cloud motions and possibly, at close range, of elevation differences of different cloud belts at the limb of the planet. High-resolution spectroscopy and/or Fourier transform spectrometry may be applicable to the detection of minute Doppler shift differentials, in addition to the general rotation of different belts as a function of latitude. It is doubtful that vertical motions will be large enough to be detected by such methods, however. If radio-reflecting transition surfaces are available, radar may be also used to measure relative motions, but the probability is that radar waves will be mainly absorbed or irregularly reflected by outer ionized layers such as in the solar corona, before any hard reflecting surface is encountered. Infrared and microwave spectroscopy and detailed thermal mapping (with at least 10 x 10 resolution elements in the disk) will provide some basic information for studies of the detailed thermal balance. Of special interest will be a search for hot-point sources at or below the visible cloud levels, possibly associated with the temporary eruptions of white spots on Saturn (the alternative that such are localized "freeze-out"—or "snow" falls—may also be considered).

4.7 EXTERNAL FIELDS

This item covers the scientific problems of the gravitational, magnetic, and electric fields surrounding the planet (or in its atmosphere) and their interaction with the solar plasma. Observables include the orbital motions of spacecrafts and natural satellites, and in particular, the quadrupole term of the gravitational field; the magnetic field strength is probably too small to produce any observable optical or radio Zeeman effect, but it should be related to the density, energies, and composition of any belt of trapped particles. It is unlikely that the outer planets have any significant net electric charge, but atmospheric activity may cause local charge separation followed by electric discharges and associated radio noise (atmospherics)-distinct from radio emission by a radiation belt or by deep-seated sources.

The remote sensors applicable to such problems include the ground-based Doppler tracking of the spacecraft orbit, nuclear precession magnetometer, microwave receiver, particle detectors of the types flown on many of the earth orbiters and planetary missions. (Whether such detectors are applicable to long-duration, deep-space missions is a technical matter that this author is not competent to discuss.) On the remote possibility that light emission accompanying electric discharges might be visible on the dark sides of the planets, direct imaging or photometric monitoring of the night side might be attempted with enough spectral and angular resolution, as well as time resolution, to distinguish between short light pulses and the more steady "night airglow" or "auroral" types of emission.

4.8 SATURN'S RING SYSTEM

Saturn's ring system raises its own special set of scientific problems, in particular the overall thickness of the ring or rings is still in great doubt with current estimates ranging all the way from a few millimeters or centimeters to several kilometers (at least). The detailed velocity distribution of the particles (in particular at right angles to the plane of the system), the particle diameter frequency function and space density in the A, B, and C rings, as well as in the major division or divisions; the reality of the finer divisions often reported and often denied; the possible existence of an extremely tenuous outermost ring (outside ring A), suspected at the times of

transits of the earth in the plane of the ring (e.g., in 1907); the nature of the surface deposit (water, ammonia ices?) that may be coating the ring particles; these are some of the many questions that remain unanswered. Perhaps the most significant and urgent is that of the thickness of the rings.

The remote sensors applicable to such problems are first the direct imaging at the closest practical range, especially if the spacecraft orbit can cross the plane of the ring near minimum distance. With a 500-mm focal length optical system and the Mariner-type Vidicon sensor, one line pair corresponds roughly to 10 arc-sec which could perhaps detect the thickness of the ring at the following ranges:

Thickness (km)	0.01	0.1	1	10	100
Range (km)	2.10^2	2.10^3	2.10^4	2.10^5	2.10^6

These nominal figures are optimistic, and in practice half the listed ranges would probably be needed for detection (measurement will require another reduction of range by a factor of 5 to 10 depending on the accuracy required). Because of quarantine requirements to minimize the probability of catastrophic encounter of outlying particles with the spacecraft, it appears that if the ring system is as thick as some recent high estimates, confirmation will be possible at minimum ranges of 10^4 km. But, if it is as thin as the low estimate limits direct, confirmation may require a special "kamikaze" mission for the spacecraft (range less than 100 km).

Other techniques applicable from safer ranges include photometry of bright stars observed through the ring system at small incidence angles (i.e., far from the plane of the ring). Such observations are marginally possible from earth and should offer no special difficulty at closer range. Ephemerides of stellar occultations (star brighter than about 7th or 8th magnitude) by the rings when the spacecraft is at distance ranges less than 10^8 km should be computed (including the possibility of adapting the spacecraft orbital path to achieve occultation of a very bright star), and precise tracking and fast data recording facilities incorporated in the photometer head and data logging system to allow high-time resolution observations of the star occultation. (Such facilities will also be essential to observe stellar occultations by the disk of the planet.) Caution should be exercised in selecting the star to avoid red supergiants with significant apparent diameters; a point source is best for the test.

At closer range, photometry and spectrophotometry of selected sections of the ring system will give the phase function and spectral reflectivity curve of the rings, including a search for characteristic diffuse absorption bands of suspected solid (ice and solid ammonia) surface coatings. High-resolution spectroscopy of selected solar lines will give precise rotation velocities (the author tends to regard this experiment as relatively unimportant since, except for satellite perturbations, and unless the particles are much smaller than anticipated, it is difficult to see how the particles can have velocities different from that corresponding to their mean distance to the center of Saturn). Of special interest to help resolve the question of the composition of the rings is the detailed thermal mapping at several wavelengths along a radius of the ring system. Radar reflectivity measurements will also be important to help derive the filling factor of different parts of the ring system.

Detailed scanning photometry along a radius of the ring near the diameter of the elliptical projection of the ring, with precise allowance for scanning rate and high angular resolution, should be used to supplement the television experiment in defining the positions of the major divisions, and to search for minor divisions (shielding against direct illumination by the globe may be needed to achieve good photometry of the inner "crepe" ring and search for the suspected division at its outer edge, i. e., between rings B and C).

If the ring particles are very small, or include a sizable population of small (i. e., micron-sized) particles, special optical effects should be looked for near the antisolar point (opposition effect, "heiligenschein", etc.) and around the direction of the sun if it can be shielded artifically or by interposition of the disk of the planet. Detection of a "corona" effect should be especially helpful to derive the frequency distribution of small particles.

5.0 SCALING FACTORS

The major scaling factors relative to the three outer planets are listed below.

5.1 GEOMETRIC FACTORS

The diameters and ellipticities are uncertain, by perhaps 1 to 3 or 5 percent and systematic errors are still difficult to assess. From recent discussions, the following values are currently the most probable estimates:

Saturn: Equatorial diameter - 120, 670 km (mean diameter = 116, 820 km
Polar diameter - 109, 110 km (= 9.17 earth mean diameter))
Ellipticity - 1/10.21
Inclination of rotation axis to orbital plane - 26 degrees, 44 minutes
Rotation period - 10 h 14 m at equator
10 h 38 m at ±45-degree latitude mean - 10 h 24 m
Mean distance to sun - 9.53885 AU

Ring system: Ring A outer diameter - 155, 000 km
Ring A inner diameter - 133, 700 km
Ring B outer diameter - 129, 500 km
Ring B inner diameter - 99, 200 km
Ring C inner diameter - 80, 100 km

Diameters are uncertain by about 1 percent in absolute value, but relative values may be consistent to 0.5 percent. Note that dynamical ellipticity (0.0979) is not in perfect agreement with optical ellipticity for the current "best" values of the diameters (0.0959).

Uranus: Mean diameter - 49, 000 ±1000 km (estimated mean error)
Ellipticity - 1/(18.0±0.6) dynamical
Inclination of rotation axis to orbital plane - 98 degrees
Rotation period (retrograde) - 10.84 ±0.16 hours (equator)
Mean distance to sun . . . 19.18228 astronomical unit (AU).

Limb darkening make diameter measurements uncertain; previous values from disk-meter observations was 47, 100 km, now believed to be undercorrected for limb darkening. Older optical data for ellipticity averaged about 1/12. Rotation period is probably more uncertain than indicated by formal estimated error of Moore and Menzel observation of 1930 which has never been successfully repeated. Because of the high inclination, Uranus is seen alternately equator-on and pole-on every 21 years; it was seen equator-on in 1966 and will appear pole-on in 1985.

Neptune: Mean diameter - 45,000 ±1,500 km (estimated mean error)
Ellipticity - 1/(58.5 ±6.2) (dynamical)
Inclination of rotation axis to orbital plane - 29 degrees
Rotation period - 15.8 ±1.0 hours (equator)
Mean distance to sun - 30.05708 AU.

Limb darkening makes optical diameter measurements uncertain. The rotation period still depends on the original observation of Moore and Menzel in 1928 which has not been checked.

5.2 DYNAMICAL FACTORS

The masses are fairly well-known from the motions of the satellites; the main source of uncertainty is the plate scale of the photographs which enters directly in the orbital radius. The harmonics of the gravitation field J and K are fairly well-determined for Saturn, J only is roughly known for Neptune, but neither can be estimated for Uranus because the orbits of the satellites are too nearly circular and exactly in the equatorial plane of the planet. Densities will vary mainly with the adopted diameter and ellipticity as does the surface gravities; the correction for the rotational centrifugal force at the equator is more precisely known. The escape velocity depends on the adopted level and temperature of the exospheric region of the atmosphere.

Saturn: Mass - 1/(3497.64 ±0.27) (sun = 1) after Hertz, 1953
Harmonics J - 0.02501 ±0.00003
K - 0.00386 ±0.00026
Surface gravity - eq. cent. force - 1044 - 176 cm sec^{-2}
Escape velocity - 37 km/sec (approx.)
Mean density - 0.68 (water = 1)

Uranus: Mass - 1/(22,934 ±6) (sun = 1), after Harris, 1950.
Harmonics - unknown
Surface gravity - eq. cent. force - 965 - 62 (cm/sec^2)
Escape velocity - 22 km/sec (approx.)
Mean density - 1.5 (water = 1)

Neptune: Mass - 1/(18,889 ±62) (sun = 1), after van Biesbroeck, 1957
Harmonics - J - 0.0074 ±0.0007
K - unknown
Surface gravity - eq. cent. force - 1427 - 27 (cm/sec^2)

Escape velocity - 25 km/sec (approx.)
Mean density - 2.2 (water = 1)

Note: Dynamical ellipticity ϵ is given by

$$\epsilon = (J + \phi/2)\ (1 + J) - K/6$$

$$J = 3\ (C - A)/2MR^2$$

where

C = moment of inertia about rotation axis

A = moment of inertia about equatorial axis

M = mass, R = radius, K = coefficient of fourth-order term of force function, and

$$\phi = \omega^2 R^3/GM$$

is the ratio of centrifugal force to gravity at equator. (For a more detailed discussion see chapter by Clemence and Brouwer in Volume III of the Solar System (planets and satellites), ed., by G. P. Kuiper and B. Middlehurst, University of Chicago Press.)

5.3 THERMODYNAMIC FACTORS

Approximate temperatures can be derived from the solar energy flux and theory or from radiometric infrared and microwave measurements of the thermal emission spectrum. The latter is fairly well-established for Saturn; there are marginal measurements for Uranus and none for Neptune.

Saturn: Solar constant at mean distance - 0.022 calories per square centimeter per minute = 1.54 $milliwatt/cm^2$
Radiometric albedo - unknown (cf. sect. 6.2), take 0.5 as a plausible guess
Mean black-body temperature of whole disk at 10 microns (8 to 14 band) - 93° K (Low, 1964)
107° K (Moroz, 1968)
in 0.1 to 1 cm range - 120° K (average)
in 1 to 10 cm range - 150° K (average)
at 21 cm - 300°K

Increase in temperature with wavelength may indicate a hot interior or, more plausibly, a special greenhouse effect in a hydrogen-methane-ammonia atmosphere, where ammonia is the only source of opacity in the microwave range, as proposed by Gulkis, McDonough, and Craft (Icarus 10, 421, 1969).

Uranus: Solar constant at mean distance - 0.0055 cal/cm^2/mn = 0.38 mW/cm^2
Radiometric albedo - unknown (cf. sect. 63.), take 0.4?
Mean black-body temperature of whole disk at 10 microns (8 to 14 band) - 85° K? (marginal)
Computed mean effective temperature
pole toward sun - 52° K?
equator toward sun - 73° K?

Neptune: Solar constant at mean distance - 0.0022 cal/cm^2/mn = 0.15 mW/cm^2
Radiometric albedo - unknown (ci. sect. 6.4), take 0.4?
Estimated mean effective temperature - 50° K?

5.4 ATMOSPHERIC FACTORS

Data on atmospheric composition refer mainly to the regions above the cloud level, some are estimates from line and molecular band absorption, others are from assumed strength of Rayleigh scattering in a pure molecular atmosphere with a plausible H/He ratio; the latter has been estimated in one case (Neptune) from the scale height derived from a stellar occultation (for an assumed temperature).

Saturn: Atmospheric composition (after Owen, 1969)
H_2 - 190 ±40 km-atm
He - presumed present with cosmic abundance (about 20 percent)
CH_4 - 350 meter-atm. (all data are for gas above the 95°K cloud tops)
NH_3 mixing ratio - 5.10^{-4}
Atmospheric depth below the 95° K cloud tops ≥ 120 km
Pressure at cloud levels - 2 to 4 atm.?

Uranus: Atmospheric composition
H_2 - 1500 km-atm? (after Belton, 1969)
He - presumed present with cosmic abundance)
CH_4 - 3 km-atm? (more frozen out)
NH_3 - frozen out

Neptune: Atmospheric composition
H_2 - bands stronger than on Uranus
He - presumed present with cosmic abundance
CH_4 - 5 km-atm?
NH_3 - frozen out.
Scale height about 1000 km above apparent surface derived from stellar occultation - 50 to 60 km
Diameter of 1/2 intensity shell in stellar occultation - 50450 ±60 km (Kovalevski and Link 1969)

Remark: The atmospheric level causing an intensity reduction of 50 percent by differential refraction must be at least 1000 km above the apparent optical edge of the planet; its diameter is an upper limit to the diameter of the planet and it may be used to derive a lower limit to the density (1.57); the optical value used in Sections 5.1 and 5.2 may lead to an upper limit of the density (2.21) if limb darkening was under-corrected.

The large intensity fluctuations observed during the stellar occultation suggests that in addition to scintillation effects, discrete absorbing layers may be present in the upper atmosphere of Neptune. (For further discussion refer to Kovalevski and Link, Astronomy and Astrophysics, 2, 398, 1969.) (The temperatures quoted in this paper seem too high and the mean molecular mass too low, unless there is a very effective mechanism for diffusive separation of H_2 and He in the higher atmospheric levels or a photodissociation of H_2 reducing the effective mean molecular mass to 2 or less.)

5.5 PHOTOMETRIC FACTORS

Many of the experiments from a space vehicle, including direct imagery, photometry, polarimetry, spectroscopy and spectrophotometry, will critically depend on scaling factors determined by the energy flux available at various wavelengths. A more detailed discussion of photometric data is given in Section 6.0, but a summary of some of the more important parameters is given here for completeness, in particular for the ordinary optical range.

Saturn: Solar flux density at mean distance - 2.20 erg cm^{-2} sec^{-1} Å^{-1}
at λ_B = 0.437μ and λ_V = 0.545μ (see note 1 below)

Visual magnitude at mean opposition - +0.67
at unit distances - 08.88 (see note 2)
Mean visual surface brightness of disk at mean distance - 6.9 mag/arc-sec^2
Mean phase coefficient of globe only - 0.015 mag/deg or less
of globe and ring - 0.04 mag/deg (variable)
Visual geometric albedo - 0.46 (globe only)
0.67 (ring only)
Mean color index B - V (blue - yellow) - 1.04 (globe only)
0.9 (ring only)
U - B (UV - blue) - 0.58 (globe only)

Note 1: these values are calculated for a solar constant of 2.00 cal/cm^2/mn at the earth and a spectral energy curve of total solar radiation corresponding to a spectral irradiance of 200 ergs per square centimeter per second and per Ångstrom at the earth.

Note 2: this is the standard value for the (fictitious) situation of a planet seen at full phase and simultaneously at unit astronomical distance from the sun and from the observer (see Section 6.1 for further details).

Note 3: for a discussion of photometric parameters of the ring of Saturn, see Section 6.2.

Uranus: Solar flux density at mean distance - 0.545 erg $sec^{-1}cm^{-2}A^{-1}$ (at 0.437 and 0.545μ)
Visual magnitude at mean opposition - +5.52
at unit distances - -7.19 (-7.16 pole on)
Mean visual surface brightness of disk at mean distance - 8.2 mag/arc-sec^2
Mean phase coefficient (linear phase law) - 0.0013 mag/deg
(quadratic law) - 0.00031 mag/deg^2
Visual geometric albedo - 0.53
Mean color index B - V - 0.56
U - B - 0.28

Note 4: for a discussion of the differences between pole-on and equator-on presentations, see Section 6.3.

Neptune: solar flux at mean distance (at 0.437 and 0.545μ) - 0.22 erg $cm^{-2}sec^{-1}A^{-1}$
Visual magnitude at mean opposition - +7.83
at unit distances - 6.88
Mean visual surface brightness of disk at mean distance - 9.6 mag/arc-sec^2
Mean phase coefficient (quadratic) - 0.0006 mag/deg^2 (?)
Visual geometric albedo - 0.44
Mean color index B - V - 0.41
U - B - 0.22

Note 5: for further discussion of the photometric parameters of Neptune, see Section 6.4.

6.0 PHASE FUNCTIONS, ALBEDOS, AND SPECTRAL REFLECTIVITIES OF THE OUTER PLANETS

Important objectives of the optical observations of the three outer planets from flyby missions will be a refinement of current knowledge on the photometric phase functions which is severely limited by the phase angle restrictions of earth-bound telescopes, the determination of their spherical albedos (impossible from earth for the same reasons), and an extension of the present limited knowledge of their spectral reflectivity curves. These elements are not only important for the construction of theoretical models of their atmospheres, and in particular their scattering properties, but also for the planning of the optical observations to be carried out from space vehicles.

Experience has shown that engineers often have difficulty in translating astronomical photometric data into more familiar physical units because of the peculiar concepts and nomenclature that have been inherited from a long tradition of astronomical photometry. The following notes on planetary photometry in general, followed by a special discussion of each of the outer planets, should prove useful in this respect.

6.1 PHOTOMETRIC UNITS AND PARAMETERS

The visual brightness and reflectivity of a planet, i.e., near $\lambda = 0.55\mu$, is still a convenient starting point in planetary photometry. The stellar magnitude of the disk seen at full phase (i.e., at exact opposition to the sun) is the basic factor to compute the geometric albedo p of the planet and its surface brightness, either in conventional visual photometric units (luminance), or in energy units (specific intensity). The phase function or law of variation of relative luminosity with phase angle (sun-planet-observer) determines the phase integral q and, in conjunction with p, the spherical albedo (also called physical albedo or Bond albedo), $A = pq$, which measures the fraction of the incident flux reflected in all directions of space (while p measures the reflection toward the source only).

A knowledge of p and q as a function of wavelength over the whole spectral range in which solar radiation is significant would provide fundamental information on the scattering properties of the atmospheres of the outer planets. Integration of the spectral reflectivity function A (λ) weighted by the source function, i.e., the spectral energy distribution of solar radiation F (λ) leads to the radiometric albedo A*. The fraction of the incident solar radiation absorbed by the planet $(1 - A^*)F$ is the fundamental quantity in the thermal equilibrium of the planet (apart from possible internal heat sources).

6.1.1 Magnitude Systems

The traditional astronomical system of stellar magnitudes m_V measures the illumination I (or visual flux density) which determines the luminous flux $\phi = IS$ received by an optical system having an aperture area S. By definition,

$$m_V = \mu_1 - 2.5 \log I \qquad (6.1)$$

The constant μ_1, called "stellar magnitude of the lux", is difficult to measure precisely because of the great differences between the color temperatures of the stars and of the primary photometric standard (black body at 2042° K). From a number of modern discussions of this problem we may accept, in the V system (see below), $\mu_1 = -13.8$, for the magnitude of a star producing an illumination of 1 lux on a screen normal to the rays outside the earth atmosphere. To produce the same illumination at sea level, a star at the zenith should have a magnitude -14.05, assuming an average extinction $k_V = 0.25$ magnitude (or a transmission of 80 percent) by the earth atmosphere on a clear day. The constant μ_1 is needed only to relate astronomical photometric units to the practical units of illumination engineering (see Section 6.0 for a brief summary); it does not enter in the calculation of albedos which require only a knowledge of the corresponding photometric constants for the sun. In practice, the zero point of the V system of stellar magnitudes does not depend on μ_1 either; it is fixed by the mean magnitude of 10 stars designated as primary standards after multiple precise photoelectric comparisons through a yellow filter approximating the visibility function of the human eye which no longer enters in the definition and measurement of so-called "visual" magnitudes (except through a long chain of historical evolution of concepts and methods). The present V system replaces the previously (1920 to 1950) used "international photovisual system", denoted IP_V, which was defined by selected stars in the so-called "North Polar Sequence"; for these stars the average zero-print difference is $V = IP_V - 0.02$; it matters only when older data need to be precisely reduced to the V system, but the 2-percent difference is hardly significant considering the lower precision of the pre-photoelectric data.

The luminance (surface brightness) of a planet can be expressed in magnitudes per square second of arc (or per square degree or per steradian), because a magnitude is basically a measure of illumination (flux density) and a luminance is a measure of illumination per unit solid angle (see Section 6.0 for definitions). Since 1 cm sub-tends 1" at a distance $\rho'' = 206,264.8$. cm, it follows that a luminance of 1 cd cm^{-2} (one candela

per sq. cm.) corresponds to $m_V'' = \mu_1 + 5 \log \rho'' = -13.8 + 16.57 = +2.3$ mag/arc-sec^2. The average luminance of the outer planets is about 5 magnitudes or 2 orders-of-magnitude fainter, i.e., of order 0.01 cd cm^{-2}.

6.1.2 Color Indices and Effective Wavelengths

As a first approximation and crude indication of spectral energy distribution in the radiation from stars and planets, astronomers have used traditionally color indices $C_{i,j}$ defined as the difference of magnitudes measured through two or more wideband color filters. By definition

$$C_{1,2} = m_1 - m_2 = -2.5 \log \frac{\int_0^\infty I(\lambda)\tau_1(\lambda)\, Q_1(\lambda)\, d\lambda}{\int_0^\infty I(\lambda)\tau_2(\lambda)\, Q_2(\lambda)\, d\lambda} \qquad (6.2)$$

where $\tau(\lambda) Q(\lambda)$ is the product of the spectral transmission factor of the optical system (telescope + filter + atmosphere) by the quantum efficiency of the detector; in other words, the "spectral sensitivity" function $S(\lambda)$ of the photometric system in which the magnitude m is measured. For the standard photometric systems U, B, V, R, I, . . . listed in Table B-1, the magnitudes are measured through filters with band-pass of 0.05 to 0.1μ half-width centered at the given wavelengths in the near ultraviolet, blue, yellow (visual), red and near-infrared, etc. The centroid or first moment of the area under the curve $I(\lambda)\tau(\lambda) Q(\lambda)$ defines the so-called "effective wavelength" λ_e of a given combination of source-filter-detector functions. The effective wavelengths in Table B-1 are calculated for the solar energy function $I_s(\lambda)$ given in Table B-2.

When it is necessary (in the absence of direct determinations) to use broadband magnitudes as approximations for narrowband or monochromatic magnitudes, the wavelength that must be assigned to the broadband values is not the effective wavelength, but the so-called "isophotal wavelength" λ_i

Table B-1. Mean, Effective*, and Isophotal Wavelengths

System	U'	U	B	V	R	I'	I	J	K	L
$\lambda_o(\mu)$	-	0.36	0.44	0.55	0.70	-	0.90	1.25	2.2	3.4
$\lambda_e(\mu)$	0.33	0.37	0.445	0.555	0.695	0.82				
$\lambda_i(\mu)$	-	0.365	0.437	0.545	0.717					
*For the source function $I_s(\lambda)$.										

Table B-2. Spectral Distribution of Solar Radiation*

$\lambda(\mu)$	$I_s(\lambda)$	$\lambda(\mu)$	$I_s(\lambda)$	$\lambda(\mu)$	$I_s(\lambda)$
0.200	1.4	0.380	123	0.65	167
0.205	1.8	0.385	115	0.70	149
0.210	2.9	0.390	112	0.75	129
0.215	4.8	0.395	120	0.80	114
0.220	6.2	0.400	154	0.85	102
0.225	7.0	0.405	191	0.90	90
0.230	7.2	0.410	194	0.95	82
0.235	6.4	0.415	197	1.00	74
0.240	6.8	0.420	193	1.05	68
0.245	7.8	0.425	182	1.10	61
0.250	7.6	0.430	179	1.15	56
0.255	11.2	0.435	190	1.20	50
0.260	14	0.440	205	1.25	45
0.265	20	0.445	216	1.30	41
0.270	25	0.450	220	1.35	37
0.275	22	0.455	219	1.40	33
0.280	24	0.460	214	1.45	30
0.285	34	0.465	208	1.50	27
0.290	52	0.470	204	1.55	25
0.295	63	0.475	204	1.60	22.3
0.300	61	0.480	202	1.65	20.4
0.305	67	0.485	194	1.70	18.5
0.310	76	0.490	190	1.75	16.7
0.315	82	0.495	191	1.80	14.8
0.320	85	0.500	192	1.85	13.7
0.325	102	0.505	192	1.90	12.5
0.330	115	0.510	192	1.95	11.4
0.335	111	0.515	189	2.0	10.2
0.340	111	0.520	188	2.5	4.97
0.345	117	0.525	192	3.0	2.63
0.350	118	0.530	195	3.5	1.78
0.355	116	0.535	196	4.0	0.93
0.360	116	0.540	199	4.5	0.67
0.365	129	0.545	199	5.0	0.41
0.370	133	0.550	198	5.5	0.31
0.375	132	0.600	187	6.0	0.21

*Total radiation emitted in a 100-A band and normalized to the solar constant of 2.00 cal cm^{-2} min^{-1}.

which is so defined that it is independent of the color of the source, i.e., of $I(\lambda)$; the isophotal wavelengths for the U, B, V, R systems are also listed in Table B-1.

A neutral or "gray" scatterer has the same color indices as the source of illumination; nongray scatterer has an intrinsic color due to selective scattering which may be measured by its "color excess" (either positive if it is redder than the source or negative if bluer) compared to the color indices of the sources measured between the same wavelengths. Planets tend to be redder than the sun, except when their reflected light is predominantly of atmospheric origin and due to Rayleigh scattering and/or (as in the case of Uranus and Neptune) when strong molecular bands suppress large regions of the yellow and red parts of the spectrum.

6.1.3 Solar Units

(Albedo calculations require a knowledge of the stellar magnitude of the sun, or at least (in principle) of the magnitude difference between the planet and the sun (it is impossible in practice to measure this difference by direct comparison because of the enormous ratio of illuminations involved). The illumination produced by the sun at a distance of one astronomical unit (1 a.u. = $1.49598 . 10^8$ km), called the "luminous solar constant" is, approximately,

$$I_s = 1.35 . 10^5 \text{ lux} = 13.5 \text{ phots} = 1.25 . 10^4 \text{ ft-candle}$$

The corresponding luminance of a perfect scattering or Lambert disk irradiated at normal incidence is

$$L_1 = 4.3 \text{ cd cm}^{-2} = 13.5 \text{ Lamberts.}$$

The energy flux density received from the sun at unit distance, or "solar constant", is very nearly

$$I_s^* = 2.00 \text{ calories per sq cm per minute}$$

or

$$\int_0^\infty I_s(\lambda)\, d\lambda = 1.40 . 10^6 \text{ erg cm}^{-2}\text{sec}^{-1} = 0.14 \text{ watt cm}^{-2}$$

The corresponding radiance of a perfect black disk in radiative equilibrium with it (at normal incidence) is

$$\int_0^\infty L_0(\lambda)\, d\lambda = 34 \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ deg}^{-2}$$

The energy distribution of this radiation is that of the black body in thermal equilibrium.

The visual magnitude of the sun at unit astronomical distance is still somewhat uncertain, perhaps by as much as 0.1 magnitude (or 10 percent in I_s). From a variety of modern re-discussions of this problem the value

$$m_s(V) = -26.80$$

may be adopted, with an estimated probable error of 0.02 or 0.03 magnitude. It is important to remember that this uncertainty in m_s is directly reflected in a corresponding uncertainty of planetary albedos.

The color indices of stars having the same spectral-type G2 V as the sun are as follows:

$$U' - V = +0.63,\ U - V = +0.70,\ B - V = +0.64,\ R - V = -0.52$$
$$I - V = -0.78,\ J - V = -1.6,\ K - V = -1.41,\ L - V = -1.53$$

The spectral energy distribution of solar radiation is known in relative values with sufficient precision for current problems of planetary spectrophotometry; Table B-2 summarizes modern rediscussions of the best data normalized to a solar constant of 2.00 cal cm^{-2} min^{-1}. The values (Figure B-1) are smoothed through a bandwidth varying from 0.005μ in the ultraviolet to 0.01μ in the infrared. The normalization factor happens to be such that the spectral irradiance at the isophotal wavelengths of the standard B and V systems ($\lambda_B = 0.437\mu$ and $\lambda_V = 0.545\mu$) is

$$I_s(B, V) = 200 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ per Ångstrom}$$

By integration of $I_s(\lambda)$ the fraction

$$k_s(\lambda) = \int_0^{\lambda} I_s(\lambda)\, d\lambda \Big/ \int_0^{\infty} I_s(\lambda)\, d\lambda$$

of solar energy radiated at wavelength shorter than λ can be computed (Figure B-2); in particular $k_s = 1/2$ for $\lambda = \lambda_s(1/2) = 0.70\mu$. In other words, half the solar energy is carried by infrared radiations of $\lambda > 0.70\mu$. This fact explains why any calculation of the radiometric albedo of the outer planets must remain highly uncertain as long as precise data on the infrared albedos are lacking.

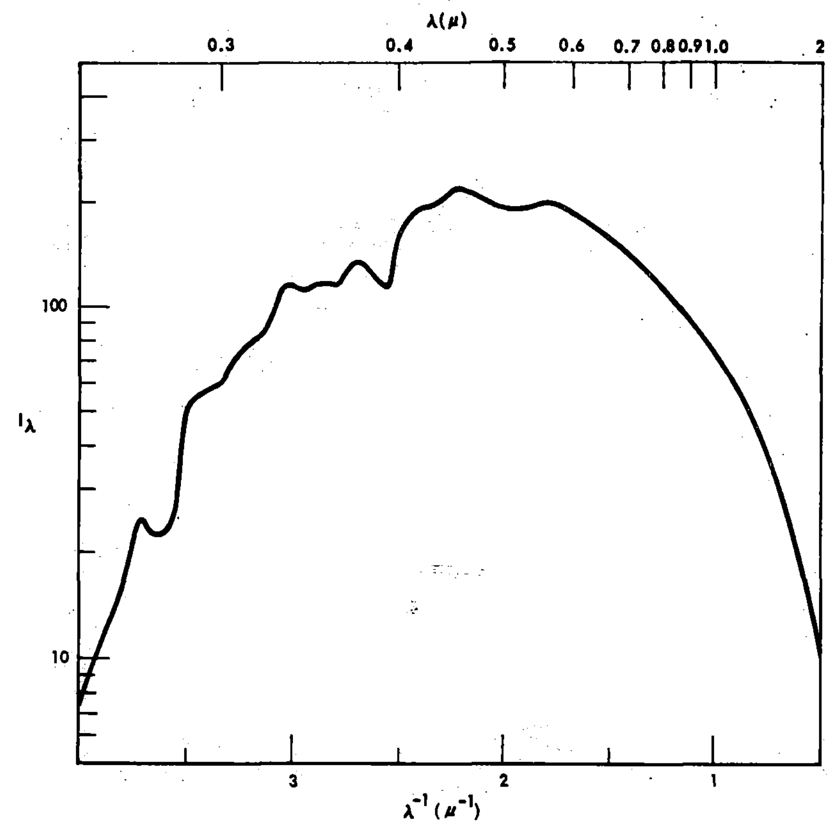

Figure B-1. Spectral Energy Distribution of Solar Radiation ($erg\ cm^{-2}\ sec^{-1}\ A^{-1}$ at 1 AU)

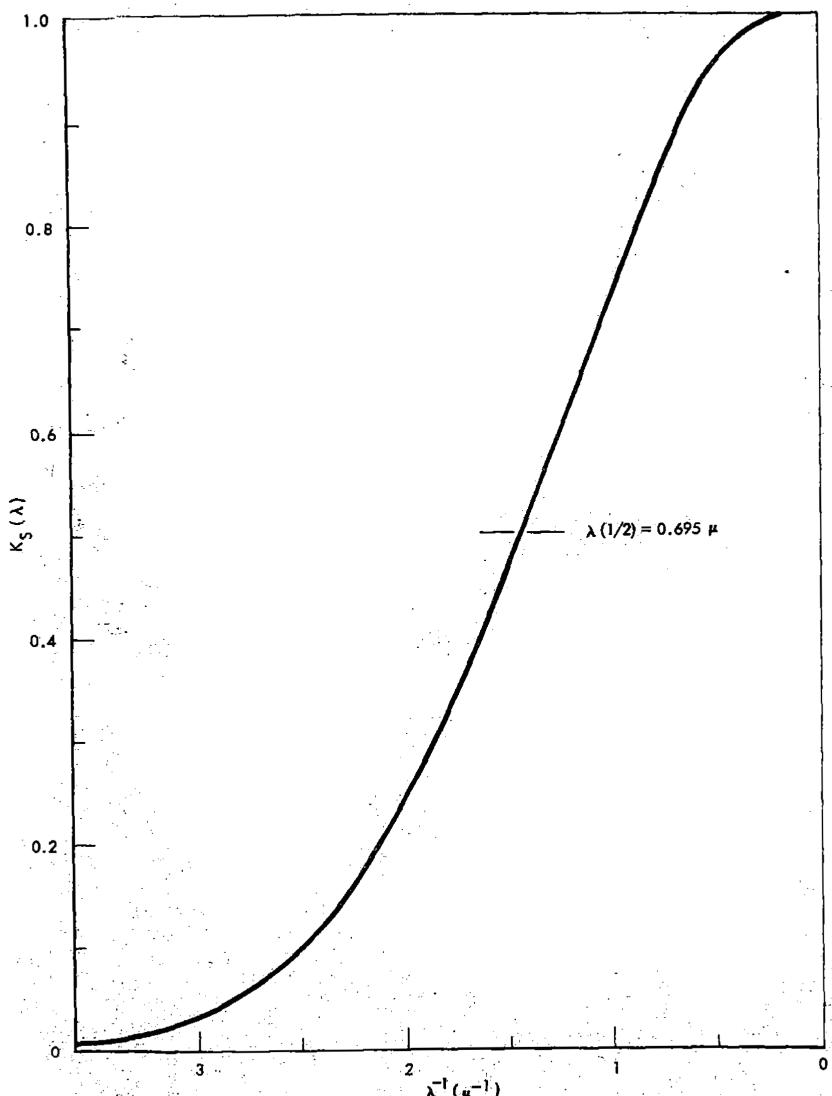

Figure B-2. Integrated Solar Radiation: Fraction of Solar Constant Emitted at $\lambda \leq \lambda K$

Space Division
North American Rockwell

6.1.4 Photometric Parameters

Reduced Magnitudes

Let I_s be the flux density received from the sun (in some spectral range) at a distance of 1 a.u.; let I(i) be the flux density received from a planet when it is at distance R from the sun and Δ from the earth, and i is the phase angle sun-planet-earth. By definition, the relation between the corresponding apparent magnitudes is

$$\log\,[I(i)/I_s] = 0.4\,(m_s - m) \tag{6.3}$$

In practice, the observed magnitudes are reduced to some standard distances, often R Δ = 1, by application of the inverse square law, i.e.,

$$I(R, \Delta, i) = I(1, 1, i)/R^2\Delta^2$$

or

$$m_1(i) = m(i) - 5 \log R\Delta$$

In particular, when i = 0 (full phase),

$$m_1(0) = m(0) - 5 \log R(0)\Delta(0) \tag{6.4}$$

This situation RΔ = 1 with i = 0 is a mathematical fiction; some astronomers prefer to reduce observations to the distances at mean opposition $R_o\Delta_o = R_o(R_o - 1)$, if R_o is the semi-major axis of the orbit (= mean distance of planet to sun). This situation is observable for the outer planets, but the convention RΔ = 1 is more commonly used and it will be adopted here. The transformation constants are easily calculated through the relation

$$m_1(R \quad = 1) = m(R_o\Delta_o) - 5 \log R_o\Delta_o \tag{6.5}$$

For Saturn, the last term is -9.558 magnitude, for Uranus, -12.717, and for Neptune, -14.711.

Phase Function

The phase function (or phase law) is defined by

$$\phi(i) = I(i)/I(0) \tag{6.6}$$

and can be calculated through

$$\log \phi(i) = 0.4\,[m_1(0) - m_1(i)] \tag{6.7}$$

This function measures the relative luminous intensity as a function of phase angle and is normalized to unit intensity at full phase (for a fixed value of $R\Delta$). The phase function may be graphed in rectangular coordinates as $m_1(i)$ or in polar coordinates as $\phi(i)$ which serves as diffusion indicatrix.

The relative mean luminance of the planet at phase i is

$$\beta(i) = L(i)/L(0) = \phi(i)/k = 2\,\phi(i)/(1 + \cos i) \tag{6.8}$$

where $k = (1 + \cos i)/2$ is the illuminated fraction of the disk. The average luminance of the disk at full phase $L(0)$ is the unit.

Geometric Albedo

It may be defined as the ratio p of the mean luminance of the planet at full phase ($i = 0$) to that of a perfect scatterer (Lambert surface) illuminated by the sun at normal incidence and at the same distance to the sun. It is also equal to the ratio of the luminous intensity of the planet at full phase to that of a Lambert disk having the same diameter as the planet and normally illuminated by the sun at the same distance R to the sun and Δ to the earth. If r is the linear radius and σ the angular semi-diameter of the planet at distance Δ, we have

$$p = \frac{I(0)}{I_s}\,\frac{R^2\Delta^2}{r^2} = \frac{I(0)}{I_s}\,\frac{R^2}{\sin^2\sigma} \tag{6.9}$$

If σ is the apparent semi-diameter at unit distance, and if we write $m_o \equiv m_1(0)$, Equations (6.1), (6.2), and (6.9) give

$$\log p = 0.4\,(m_s - m_o) - 2 \log \sin \sigma_1 \tag{6.10}$$

When, as in the case of the outer planets, the disk is not circular, σ_1 must be replaced by the radius σ_1' of the circle having the same projected area. If the observer is placed in the equatorial plane of a planet having ellipticity $f = 1 - (b/a)$, where a, b = equatorial and polar radii, then

$$\sigma_1' = \sigma_1\,(1 - f)^{1/2} = \sigma_1(1 - 1/2f) \tag{6.11}$$

The difference between σ_1 and σ_1' approaches 5 percent for Saturn.

Taking into account the relation $\sin\sigma = r/\Delta$ and the approximation $\sigma = \sin\sigma$ for the small apparent diameters of all planets as seen from earth (not from a flyby), we have in seconds of arc $\sigma'' = \rho'' r/\Delta$, where $\rho'' = 1/\sin 1'' = 206,264.8$. (When $\Delta = \Delta_1 = 1$ a.u., $\sigma = \sigma_1'' = \rho'' r/\Delta_\nu$). By substitution in Equation (6.11) we obtain the practical formula

$$\log p = 0.4\,(m_s - m_o) - 2 \log (\sigma_1''/\rho'') \tag{6.12}$$

where σ_1'' is the apparent semi-diameter at unit distance and $\log \rho'' = 5.314425$.

The luminance of a Lambert disk illuminated by the sun at normal incidence and at a distance of 1 a.u. is

$$L_1 = I_s/\pi \tag{6.13}$$

The average luminance of a planet at full phase and at distance R from the sun is, from Equations (6.9) and (6.13)

$$L(0) = p\,L_1/R^2 = I(0)/\pi \sin^2\sigma \tag{6.14}$$

Phase Integral and Spherical Albedo

The spherical (or Bond) albedo $A = pq$ is the ratio of the total luminous flux reflected by a sphere in all directions to the flux intercepted by the sphere in a parallel beam of light. The phase integral q is, by definition,

$$q \equiv \int_0^{2\pi} \phi(i) \sin i \, di \tag{6.15}$$

If the phase law $\phi(i)$ is symmetrical with respect to the direction of incidence

$$q = 2\int_0^{\pi} \phi(i) \sin i \, di \tag{6.16}$$

For an ideal sphere obeying the Lambert scattering law $L = L_1 \cos \epsilon'$ where ϵ' is the angle of incidence, the phase function is

$$\phi_o(i) = \frac{1}{\pi}\,[\sin i + (\pi - i) \cos i] \tag{6.17}$$

and

$$q_o = 3/2.$$

Since the albedo of a perfectly scattering sphere is, by definition, $A_o = 1$, it follows that $p_o = A_o/q_o = 2/3$ (NOT 1!), and that the average luminance of a Lambert sphere at full phase and at unit astronomical distance from the sun is

$$L_o = \frac{2}{3} L_l = \frac{2}{3}\frac{I_s}{\pi} = 0.2122\ I_s \tag{6.18}$$

For a real planet the ratio L_o/I_s is called the brightness factor. No planet obeys the Lambert phase function, but according to some theoretical models the outer planets could have phase functions leading to phase integrals of the order of 1.4 to 1.7; verification or otherwise will be a suitable task for the flyby missions in their cruise phases.

Radiometric Albedo

From the monochromatic magnitudes $m(\lambda)$ and $m_s(\lambda)$, we can derive the spectral reflectivity function $l(\lambda)$ and the spectral variation of the phase integral $q(\lambda)$, and finally of the spectral spherical albedo $A(\lambda) = p(\lambda).q(\lambda)$. If $I_s(\lambda)$ is the spectral energy distribution function of solar radiation, the integral geometric albedo or "radiometric albedo" is

$$p^* = \int_o^\infty p(\lambda) I_s(\lambda)\, d\lambda / \int_o^\infty I_s(\lambda)\, d\lambda \tag{6.19}$$

and the radiometric phase integral

$$q^* = \int_o^\infty q(\lambda) I_s(\lambda)\, d\lambda / \int_o^\infty I_s(\lambda)\, d\lambda \tag{6.20}$$

The integral or radiometric spherical albedo is

$$A^* = p^* q^* \tag{6.21}$$

is the fundamental quantity in theoretical studies of the heat balance of the planet. The total energy flux absorbed by the planet in the solar radiation field is

$$F^* = (1 - A^*)\,\pi r^2 (I_s^*/R^2) \tag{6.22}$$

where I_s^* is the terrestrial solar constant (in erg cm^{-2} sec^{-1}, r the planetary radius (in cm) and R the distance to the sun (in a.u.).

Unfortunately, the functions $p(\lambda)$ and $q(\lambda)$ are still very poorly known or completely unknown in the infrared for the outer planets and the calculation of the integrals in Equations (6.19) and (6.20) is not yet possible, except as to rough order-of-magnitude. It will be important to obtain the necessary observations from space vehicles.

Spectral Irradiance

The monochromatic energy flux density or spectral irradiance received from a planet at unit distance ($R\Delta = 1$) and at full phase ($i = 0$) is given by

$$\begin{aligned} \log I_o(\lambda) &= \log I_s(\lambda) + 0.4\,[m_s(\lambda) - m_o(\lambda)] \\ &= \log I_s(\lambda) K(\lambda) \end{aligned} \tag{6.23}$$

It is convenient to normalize this quantity to the isophotal wavelength $\lambda_V = 0.545\mu$ of the V system, where

$$I_o(V) = I_s(V) K(V) \tag{6.24}$$

with $I_s(V) = 200$ ergs cm^{-2} sec^{-1} Å^{-1} and, as above, $I_o = I(i = 0,\ R\Delta = 1)$. Then, at any given wavelength,

$$\begin{aligned} I_o(\lambda) &= I_o(V)\,[I_s(\lambda)K(\lambda)/I_s(V)K(V)] \\ &= I_o(V)\,[I_s(\lambda)p(\lambda)/I_s(V)p(V)] \end{aligned} \tag{6.25}$$

At some other phase and distances, the spectral irradiance at λ_v is

$$I_v(i, R\Delta) = I_v(0, 1).\ \phi_v(i)/R^2\Delta^2 \tag{6.26}$$

and at any other wavelength it is

$$I_\lambda(i, R\Delta) = I_v(i, R\Delta).\ [\phi(i)/\phi_v(i)]\,[I_s(\lambda)/I_s(V)] \tag{6.27}$$

If, then, a planet is observed through an optical system of aperture area S, focal length F, and transmission factor $T(\lambda)$ (including the earth atmosphere if ground-based), the energy flux incident upon the image of the disk is

$$j_\lambda(i, R\Delta) = \frac{S}{R^2\Delta^2} I_o(V)\phi_i(V) \int_o^\infty \frac{\phi_i(\lambda)}{\phi_i(V)} \cdot \frac{I_s(\lambda)}{I_s(V)} \cdot \frac{p(\lambda)}{p(V)} \cdot T(\lambda)\, d\lambda$$

and the average flux density in the image of surface s is

$$\frac{j_\lambda}{s} = \frac{j_\lambda}{\pi(\sigma F)^2 k(i)} = \frac{S}{\pi F^2 \sigma_1^2} \frac{\phi_i(V)}{k(i)} \frac{I_o(V)}{R^2} \text{ times the same integral}$$

where k(i) is the illuminated fraction of the disk. The last two expressions are basic to the calculation of the energy available for optical observations from space vehicles.

The following sections will review the best current information on the basic parameters applicable to the three outer planets which will be needed for the planning of optical observations (photographic, photometric, polarimetric, and spectroscopic) from the flyby missions. This review is based on a recent rediscussion by the author of all available data; detailed references to the original papers which would be superfluous in the present survey are not included, but publication dates are noted where appropriate.

6.2 SATURN

6.2.1 Phase Function and Visual Albedo of the Globe

The photometry of Saturn is complicated by the presence of the ring. Visual observations by Muller at Potsdam, covering a half-revolution of the planet during the second half of the 19th century, led him to the following empirical correction formula

$$\Delta m_v = +2.60 \sin B - 1.25 \sin^2 B \qquad (6.28)$$

where B is the latitude of the earth with respect to the plane of the ring. Application of this correction to the observed magnitude of the Saturnian system gives the magnitude of the globe alone. In contradistinction to the earlier conclusions of Becker (1933, 1948), Harris (1961) found that the magnitude of the globe of Saturn at mean opposition is a constant within the accuracy of the data (±0.05 magnitude or 5 percent). The mean value between 1862 and 1952, according to the visual measurements of Zöllner (1865) and Muller (1893) and the photoelectric observations of Kuiper and Harris (1952) is $V_o = +0.67$, corresponding to $V_1(0) = -8.88$.

The phase effect is linear in the small range of observable phase angles $i < 6$ degrees and for the total saturnian system $a_v = 0.044$ mag/deg, after Muller (1893). Photoelectric observations by Guthnick and Prager (1918 to 1921) give similar values: 0.033 in 1914, 1915, and 1917, 0.043 in 1918 and 0.049 in 1920. Schönberg (1921) showed that this high value of the coefficient is due mainly to the phase function of the particles in the ring; the phase coefficient of the globe alone is probably not much greater than 0.01. A rediscussion of the Franklin and Cook measurements (see below) gives for

the globe alone phase coefficients of 0.013 mag/deg in the blue and 0.015 mag/deg in yellow light. Horak (1950) has computed a theoretical value of 0.005 mag/deg for a phase function consistent with the limb-darkening law in yellow light. Provisionally, one may adopt 0.01 as a plausible approximation of the phase coefficient in visible light for the globe of Saturn.

There is no detectable longitude effect in the apparent luminosity of Saturn; its amplitude was less than ±0.01 magnitude in 1914, 1915, and 1917, according to photoelectric observation by Guthnick and Prager. However, a slight effect may be observable during the temporary apparitions of white eruptions on the planet.

The geometric albedo corresponding to $V_1(0) = -8.88$ for a mean diameter of 116,820 km is $p_v = 0.46$ (very nearly the same as that of Jupiter, and close to the values for Uranus and Neptune). As explained above, the phase integral cannot be computed, except hypothetically for some assumed atmospheric model; with the indicative value $q_v = 1.5$, the spherical albedo is $A_v = 0.69$.

6.2.2 Phase Function and Visual Albedo of the Ring

The most recent and complete study of the Saturnian system is that of Franklin and Cook (Astron, J., 70, 704, 1965). By combining photoelectric measurements of the total light of the system in the U, B, V, and R photometric systems with detailed photographic photometry in the same colors on photographs taken between May and September 1959, Franklin and Cook were able to rigorously resolve the raw data into separate phase curves for the globe alone and for the ring alone, corrected for their mutual obstruction. The phase curves of the total light of the planet (Figure B-3) show a definite opposition effect (i.e., a spike above a linear extrapolation of the phase curve) at phase angles $i < 2$ degrees. Most of this effect is caused by the scattering law of the particles of the ring, as shown by Figure B-4 which gives the phase curves of the ring alone in the B and V color bands. In the interval $2^\circ\!.5 < i < 5^\circ\!.5$, the phase coefficient is 0.036 mag/deg in both colors; at exact opposition (i = 0 degrees) the excess above a linear extrapolation of the phase law is 0.28 magnitude in B and 0.23 magnitude in V.

Through a combination of the phase functions in Figure B-4 with photographic measurements of the respective areas and relative luminances of the various zones of the ring system (A, B, and C), Franklin and Cook computed the absolute surface brightnesses in magnitude per sq arc-sec at exact opposition given in Table B-3, which refers to the opposition of 1959 when the elevations of the sun and earth above the plane of the ring was about 26 degrees. Values computed for a Lambert surface at the same distance from the sun are listed for comparison.

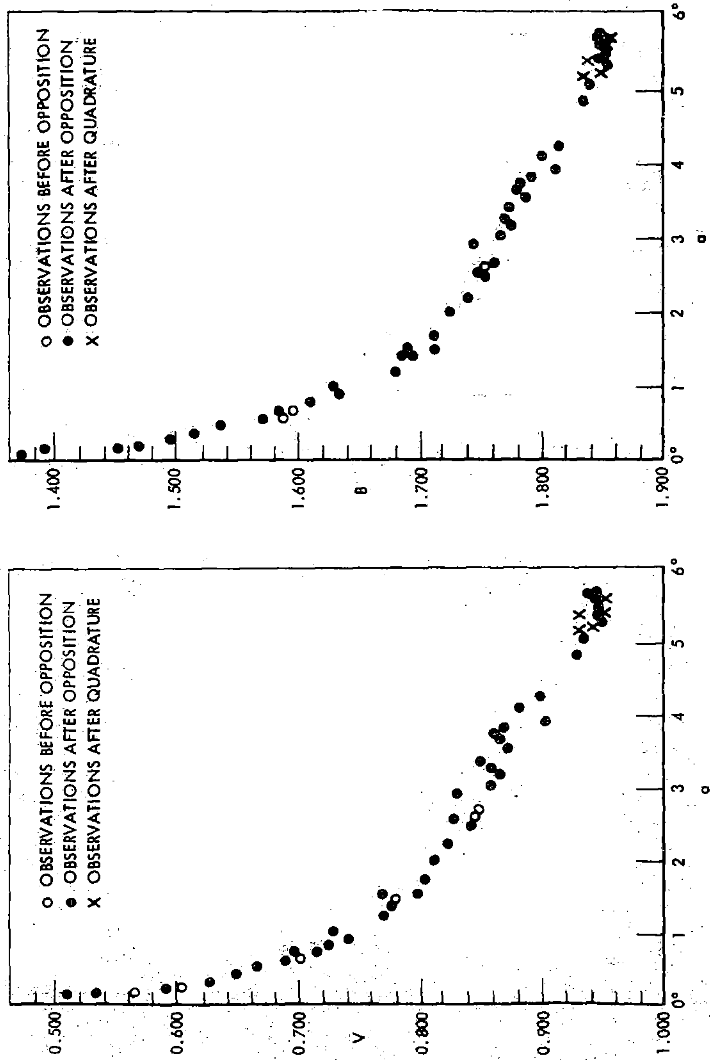

Figure B-3. Phase Functions of Saturn in V and B Near the Opposition of 1959 (After Franklin and Cook)

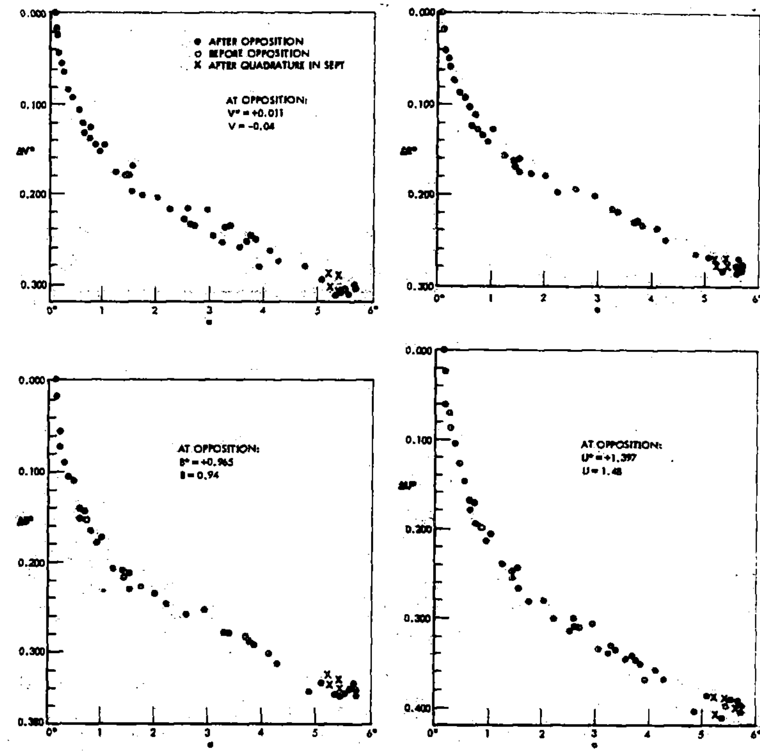

Figure B-4. Relative Phase Functions $m-m_o$ of Saturn in U, V, B, and R (After Franklin and Cook)

The phase coefficient of the ring and the opposition effect prove that it differs greatly from an orthotropic scatterer obeying Lambert's law. By analogy with the phase curves of the moon and Mercury, which have a similar behavior at small phase angles, Franklin and Cook adopted q = 0.574 for the value of the phase integral of the ring. Then, in order to compute the spherical albedo A = pq and the optical thickness τ of the various zones of the ring, Franklin and Cook used Chandrasekhar's theory of multiple isotropic scattering in the form

$$\frac{I}{\pi F} = \frac{\mu' A}{4\pi q (\mu + \mu')} \left[1 - e^{-\tau\left(\frac{1}{\mu} + \frac{1}{\mu'}\right)} \right] + u(\tau, A) \qquad (6.29)$$

where I is the observed specific intensity, πF the incident solar flux, μ, μ' the sines of the elevation angles of the sun and earth above the plane of the ring and $u(\tau, A)$ a correction for scattering of higher order than the first. Extrapolation of the observed phase law to i = 0 degrees (excluding the opposition effect) leads to $A_V = 0.67$ and $A_B = 0.54$ for the albedo of the particles in all zones of the ring and to the values of τ listed in Table B-3. The only part of the ring which is optically thick is part B, the brightest; the outer ring A is semi-transparent, a fact which is confirmed by direct observations of stars and of the globe of Saturn through this zone.

The values of A_V, A_B above indicate that the ice cover of the particles in the ring, proposed by Kuiper (1952, 1957), is incomplete or that the albedo of the ice is reduced by an admixture of impurities. This conclusion is strengthened by the fact that the ring is redder than the sun for which B - V = + 0.64, while the color index of the ring is B - V = + 0.86 at opposition, and B - V = + 0.91 outside opposition.

Table B-3. Surface Brightness of the Ring of Saturn*

Zone	A_1	A_2	B_1	B_2	B_3	Lambert
V	7.20	6.69	6.35	6.47	6.80	5.67
B	8.06	7.55	7.21	7.33	7.66	6.28
τ	0.17	0.36	1.00	0.61	0.32	—

*In mag/arc-sec^2 at 1959 opposition (B, V); third line is optical thickness

The opposition effect may be explained at least qualitatively by the interplay of mutual shadowing and occultation of the particles by each other when the direction of observation approaches closely the direction of incidence. Figure B-5 compares the light curve of the ring corrected for the linear phase effect (i.e., it shows the excess of light with respect to a linear extrapolation of the phase law) to values computed for two models of the particle density in ring B ($\tau \approx 1.0$) in which the correction for multiple scattering accounts for about one-quarter of the observed luminosity. The B and V data agree fairly well with a model formed of particles having a mean radius of 0.3 mm and filling a fraction $D \approx 4 \times 10^{-3}$ of the volume of the ring. In ring A, $\tau \approx 0.4$, $u(\tau, A) \cong 0.1$ and $D \approx 6.10^{-3}$ IF the particles have the same mean radius. According to Franklin and Cook, the actual geometric thickness of the ring is only 4 centimeters in ring A and 10 cm in ring B. Opik (1967) has argued that such a low value is difficult to accept; it is much less than values of the order of 1 to 10 kilometers derived by several authors from photometric observations of the ring seen edge-on at times of transit of the earth through the plane of the ring.

The total mass of the ring, according to this analysis, may be of the order of 2×10^{19} grams according to Opik (1967), after correction of the value 10^{13} grams originally published by Franklin and Cook.

6.2.3 Color Indices and Spectral Reflectivity

Values of the color indices U - B and B - V, observed by Hardie (Harris 1961) and by Franklin and Cook (1965), are listed in Table B-4 together with corresponding values of the geometric albedos p_λ. Data on the infrared reflectivity are still very scarce; one observation by Kuiper (quoted by Harris 1961) shows that the albedo at $\lambda = 2\mu$ is about 0.47 for the globe and 0.45 for the ring OF the still unknown values at $\lambda = 1\mu$.

Table B-4. Spectral Reflectivity of Saturn

	U - B	B - V	i	Source
Globe	0.58	1.04	?	Harris (1961)
Globe + ring	0.56	0.98	0°	Franklin & Cook (1965)
	0.62	1.01	5°	
Ring	-	0.86	0°	
	-	0.92	5°	
	U	B	V	Source
Globe p_λ	0.21	0.32	0.46	Harris (1961)
Ring p_λ	-	0.54	0.67	Franklin & Cook (1965)

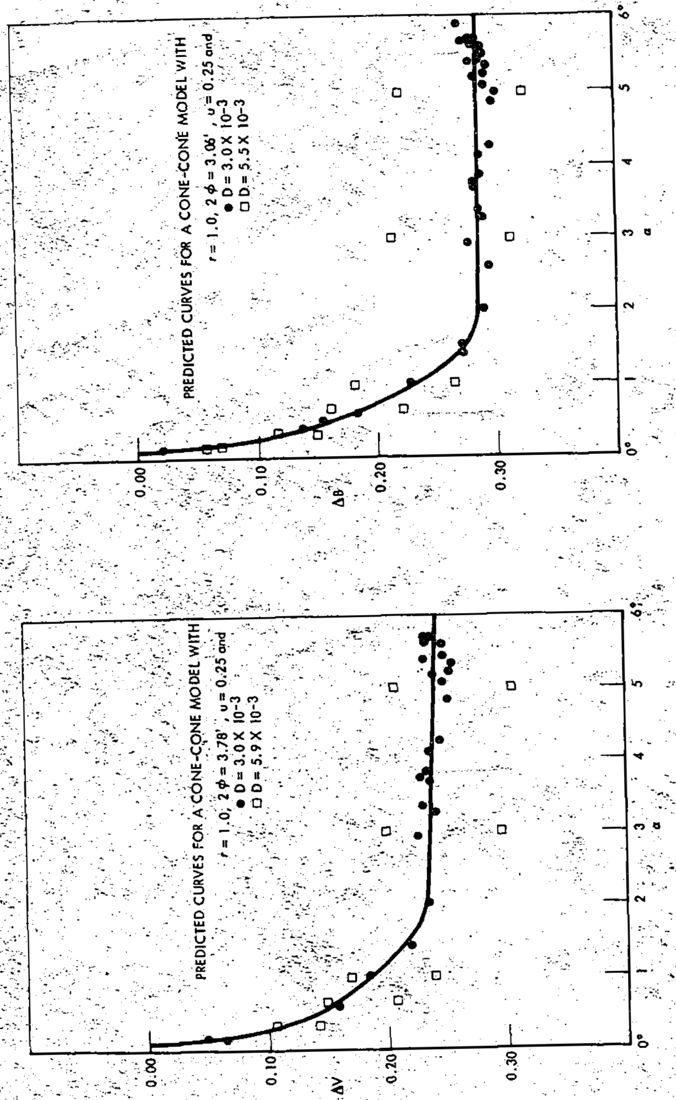

Figure B-5. Opposition Effect of Saturn's Rings in V and B Compared With Calculated Values (After Franklin and Cook)

Space Division
North American Rockwell

6.3 URANUS

6.3.1 Phase Function and Visual Albedo

The most complete and recent data on the photometry of Uranus are byproducts of a long-range program carried out in the 1950's at Lowell Observatory in a search for solar flux variations by photometric monitoring of Uranus and Neptune (Sinton 1959, Johnson and Iriarte 1959, Serkowski 1961, and Jerzykiewicz and Serkowski 1966). Older observations, whether visual or photographic, were probably not precise enough to detect a very small phase effect in the observable range of phase angle $i < 3$ degrees. The only previous photoelectric observations by Stebbins and Jacobsen (1928) gave 0.0028 mag./deg., more than twice the value that would be indicated by the Flagstaff data for a linear phase law, about 0.0013 mag./deg. (The observed variation in B color is only 0.003 to 0.004 magnitude between opposition and the maximum phase angle 3 degrees.) However, theoretical calculations by Talley and Horak (1956) for a thick atmosphere with isotropic scattering and unit albedo (not a good model, incidentally, if the emergent flux is mainly due to molecular scattering) suggested that the phase law should be quadratic with a phase coefficient 0.00020 mag./deg^2; accordingly, Sinton fitted the Flagstaff data in the B band for 1952 and 1953 to 1957 and 1958 by a quadratic term leading to a phase coefficient 0.00031 ± 0.00006 mag/deg^2. The correct phase function for Uranus can be derived only from flyby missions.

Older visual and photographic observations had on several occasions been interpreted by a longitude term synchronized with the 10 hr 50 min spectroscopic rotation period. This result is not confirmed by the modern photoelectric data (Harris 1961). Likewise, long-term variations in the mean magnitude at opposition, reported by Becker (1948), could not be confirmed by modern data, except for those of much smaller amplitude due to the variable presentation of the spheroidal globe (see Section 6.3.2). A discussion of observations prior to 1955 (Harris 1961) gave $V_1(0) = -7.19$ and $V_o = +5.52$, corresponding to $p_v = 0.53$ for the adopted mean diameter of 49,000 km (Section 5.1).

6.3.2 Ellipticity and Limb Darkening Effects

The long series of observations at Lowell Observatory between 1950 and 1966 has been analyzed by Jerzykiewicz and Serkowski (1966) who showed that not only the ellipticity, but also the limb-darkening law must be taken into account. Furthermore, the darkening coefficient may be different along the equator and toward the poles. Under the circumstances, they decided to reduce all observations to the pole-on presentation of Uranus, even though the equator-on presentation is the standard adopted for all other planets.

For a uniform disk, the ellipticity correction simply measure the ratio of the projected areas, expressed in magnitudes,

$$\Delta m_a = 1.25 \log \left[1 - (1 - b^2) \cos^2 (\theta_1 - L)\right] \quad (6.30)$$

where $b^2 = 0.833$ is the square of the ratio of the polar and equatorial axes (note that this value, used by J & S, is not consistent with the value adopted in Section 5.1 but with older optical data on the ellipticity), $\theta_1 = 166°53$ (for the equinox of 1950) is the longitude of the node of the orbits of the satellites of Uranus on the equator of the earth (one assumes that the equator of Uranus coincides with the plane of the satellite orbits), and L is the geocentric longitude of Uranus given by the American Ephemeris.

The correction Equation (6.30) does not suffice to make the B magnitude of Uranus a constant throughout the 15-year span of the observations. A residual variation, amounting to a 0.04 magnitude change (luminosity increasing with time), must apparently be attributed to differences in the limb-darkening laws in longitude and latitude. The limb-darkening coefficients X = 1.2 along the equator and Y = 0.2 along the meridians will make the reduced B magnitude of Uranus a constant between 1950 and 1966 while the presentation of the planet was changing from nearly pole-on to equator-on.

Application of these corrections to the V and B magnitudes gives $V'' = +5.56$, $B'' = +6.08$ for the mean apparent magnitudes of Uranus in polar presentation at the mean opposition (r = 19.191 a.u.), or for the standard conditions, $V_1''(0) = -7.16$ and $B_1''(0) = -6.34$. These values differ little from those resulting from the Harris (1961) discussion of earlier data (except for the revision of the diameter).

6.3.3 Color Indices and Spectral Reflectivity

Available data on color indices are listed below; the first line is from Harris' (1961) discussion of observations by Hardie, the second line is from Sinton's (1959) discussion of the Flagstaff observations:

Uranus	U - B	B - V	V - R	R - I
(1)	0.28	0.56	- 0.15	-0.80
(2)	0.26	0.55		

Further, according to Kuiper, $I(2\mu/I(1\mu) = 0.66$. The spectral reflectivity curve derived from these data is given by Figure B-6. Uranus is much darker in the infrared than most other planets (except Neptune), probably because of an accumulation of molecular bands. The blue-green color of the planet is also due in part to this effect, although Rayleigh scattering by

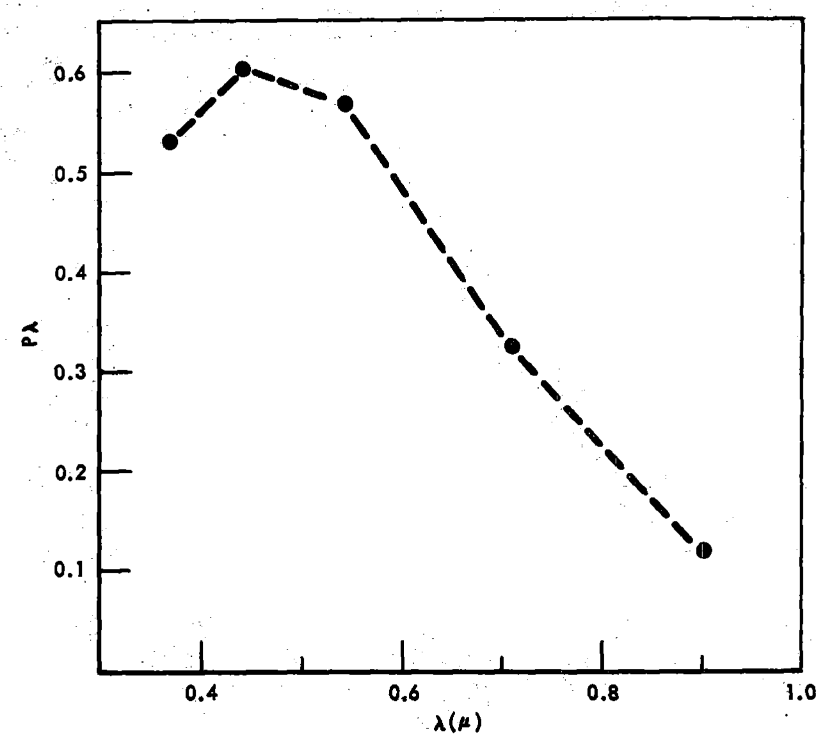

Figure B-6. Spectral Reflectivity Curve of Uranus (Ordinates Should be X 53/57 to Allow for Correction of p_v)

the molecular atmosphere may also play an important role. For Rayleigh scattering, the phase integral should be q ≅ 1.25, as compared with q = 1.45 for isotropic scattering (Harris in his classical discussion of 1961 adopted q_V = 1.65 for the four major planets, but this could lead to A ≅ 1, which is almost certainly impossible). As long as the phase integral and the infrared reflectivities are essentially unknown, it is impossible to compute the radiometric albedo (take 0.4 as a guess, if necessary).

6.4 NEPTUNE

6.4.1 Phase Function and Visual Albedo

Data prior to 1955 were discussed by Harris (1961). As in the case or Uranus, secular or periodic variations suspected by earlier authors in the old visual and photographic observations were not confirmed by modern photoelectric data. The mean of 13 oppositions between 1864 and 1954 gave $V_1(0)$ = -6.87 and V_o = +7.84, corresponding to p_V = 0.44 for the adopted diameter of 45,000 km (Section 5.1).

The most recent and extensive series of observations is again the Lowell observatory photoelectric photometry covering 1954 to 1956, analyzed by Sinton (1959), and by Jerzykiewicz and Serkowski (1966). The maximum phase effect ($i < 1°9$) does not exceed 0.001 magnitude. Nevertheless, following the theoretical model of Talley and Horak (1956) - predicting a quadratic phase law for isotropic scattering - Sinton (1959) derived with marginal significance a coefficient 0.00060 ±0.00025 (p.e.) mag./deg^2 which is of the same order as the theoretical value 0.00020. Again, this problem will be solved only by new observations from flyby missions providing a large range of phase angles.

The mean magnitude, reduced to the opposition of 1950, which may be derived from the Lowell observations of 1954 to 1966 is V_o = +7.82 (r = 30.0707 a.u.), which corresponds to $V_1(0)$ = 0.43, in close agreement with Harris' discussion of the older data.

6.4.2 Color Indices and Spectral Reflectivity

Available data on color indices are listed below; the first line is from Harris' (1961) discussion of observations by Hardie, the second line from Sinton's (1959) discussion of the Flagstaff observations:

Neptune	U - B	B - V	V - R	R - I
(1)	0.21	0.41	-0.33	-0.80
(2)	0.23	0.41		

The agreement is good. Neptune is slightly bluer than Uranus; the infrared albedo must be low as in the case of Uranus but direct data are still lacking. The spectral reflectivity curve derived from these data and for the visual albedo is shown in Figure B-7. As in the case of Uranus, any calculation of the radiometric albedo must be strictly hypothetical (if required, and as a guess, take 0.4).

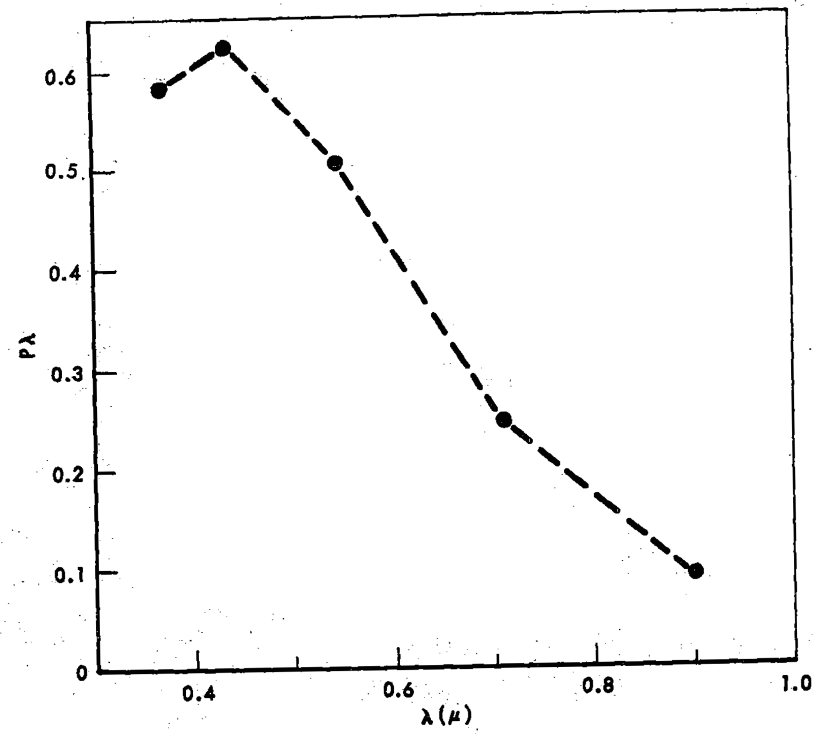

Figure B-7. Spectral Reflectivity Curve of Neptune (Ordinates Should be X 46/51 to Allow for Correction of p_V)

OBSERVATIONAL REQUIREMENTS FOR STUDIES OF THE ATMOSPHERES OF THE OUTER PLANETS

Reginald E. Newell

INTRODUCTION

The general objective of the study reported herein is to define the observation and measurement requirements for planetary exploration appropriate to remote sensing of the atmospheres of the outer planets from flyby or orbiting unmanned spacecraft. The general knowledge requirements are first formulated drawing upon our more extensive knowledge of the earth's atmosphere. These are generally the same as those put forward by the Space Science Board (1969) but the implementation suggested in terms of specific missions is not the same.

SCIENTIFIC KNOWLEDGE REQUIREMENTS

Basically we should like to understand how each planetary atmosphere works. In the case of the earth the operational mode is different in the troposphere, stratosphere, mesosphere, and thermosphere. Similar differences are to be expected for the outer planets. The appropriate questions are: (1) what are the heat sources and sinks for each layer in the atmosphere? (2) How do the heat sources and sinks generate available potential energy for the atmosphere? (3) How is this available potential energy converted into kinetic energy? (4) How is the kinetic energy redistributed, and finally dissipated in the atmosphere?

In order to study the energy cycle we need to know the temperature, density, wind, and composition as a function of latitude, longitude, height, and time. It should be noted that variations with latitude and longitude are just as important as variations with height as for some aspects of the energy cycle.

Some of the specific items required for these questions are listed below.

QUESTION 1

In the earth's atmosphere the main sources and sinks are radiative processes, latent heat, and a boundary layer flux from the underlying surface. The three terms are of the same order of importance in the troposphere with latent heat dominating the overall picture (latent heat release at low latitudes provides the main mechanism whereby the air at low latitudes is kept warmer than that at middle latitudes). In the stratosphere and higher layers, radiative processes dominate the heat sources and sinks but motions driven from the troposphere play a substantial role in determining the temperature distribution at least up to 50 km.

For the outer planets, then, we need to know the distribution of solar radiation with wavelength as a function of depth or alternatively the distribution of UV absorbers, the distribution of infrared absorbers as a function of depth, together with temperature and pressure and the distribution of substances which may contribute to the heat balance through latent heat effects. In addition, the boundary layer heating should be determined; indications are that this may play a greater relative role for the outer planets with their possible internal heat sources than for the earth.

As points of reference for the terrestrial atmosphere, we note that computations of the heating rates from solar absorption and infrared transfer for the 30 to 100 km region have been made by Murgatroyd and Goody (1958) and the infrared portion has been brought up to date recently by Kuhn and London (1969). Heating rates at higher levels were presented by Mahoney (1966) and Lagos (1967), who were interested in explaining the circulation of the thermosphere. Rodgers (1967) has computed the total radiative heating rates for the surface to the 10-mb region. A summary of the total heating rates for the 0 to 30-km region, including latent heat and boundary layer contributions, was presented recently at the London Conference on the Global Circulation of the Atmosphere (Newell, et al., 1970). Figure B-8 represents the results and could be regarded as a goal for all planetary atmosphere studies.

QUESTION 2

Knowledge of the temperature pattern in addition to the pattern of heating and cooling is required. From Figure B-8, it can be seen that more heating occurs where the atmosphere is warm, tending to increase the available potential energy.

QUESTION 3

Knowledge of the motion field is required on all scales at which conversion may occur. When air flows down the pressure gradient, work is done on the air and its kinetic energy increases. An alternative formulation involves warm air rising and cold air sinking. In general, it is very difficult to measure the vertical motions, even in the earth's atmosphere, and deductions from the horizontal motions seem to offer the best possibility.

The strongest clue to the motion fields is in the presence of banded cloud structure on Jupiter, Saturn, and Uranus; the resemblance is clearly to terrestrial Hadley cells rather than to the perturbed wave circulations of terrestrial middle latitudes. Streamlines for the terrestrial case appear in Figure B-9 (from Newell, et al., 1969); clouds accompany the rising arms and the sinking regions are clear. The cell picture is based on measurements of north-south motions averaged around latitude circles; the pattern shifts with longitude owing to the land-sea distribution. The inference for the outer planets would be a surface structure not extensively broken by north-south barriers. The kinetic energy of the circulation is derived from the heating in the rising arm of the cell by latent heat release. Presumably on Jupiter and Saturn it would be the 300 cal/gm for ammonia or the value appropriate to ammonia in solution rather than the 600 cal/gm for water vapor.

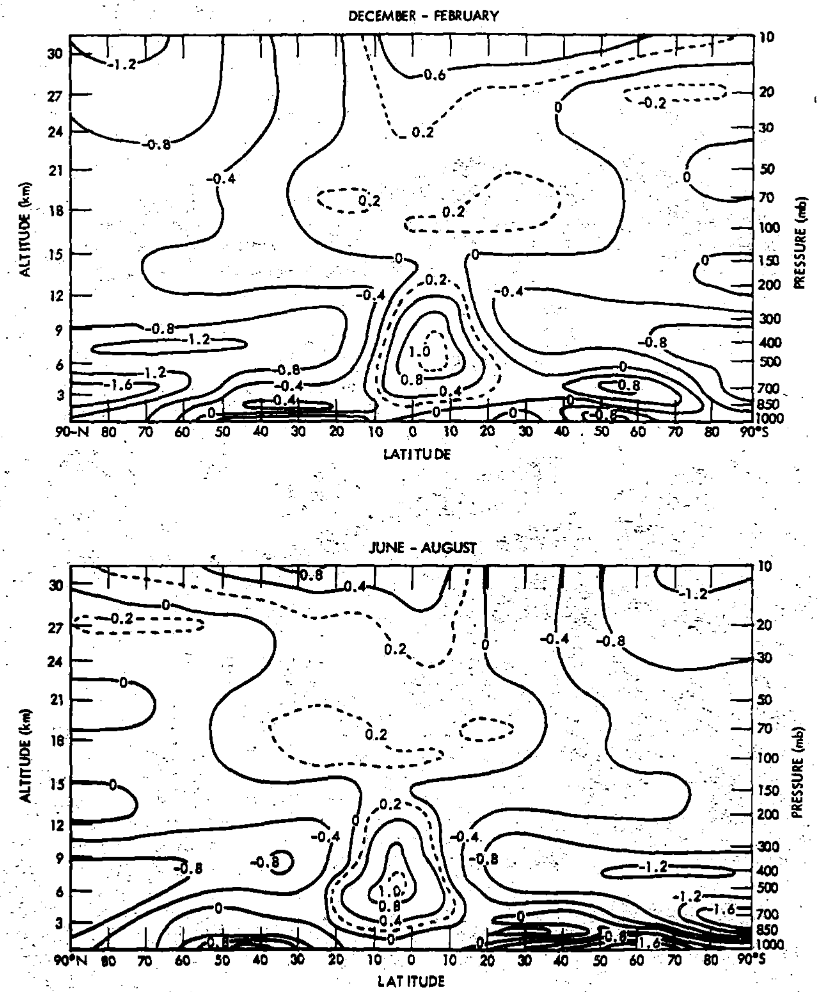

Figure B-8. Total Heating Rates (deg K/day)

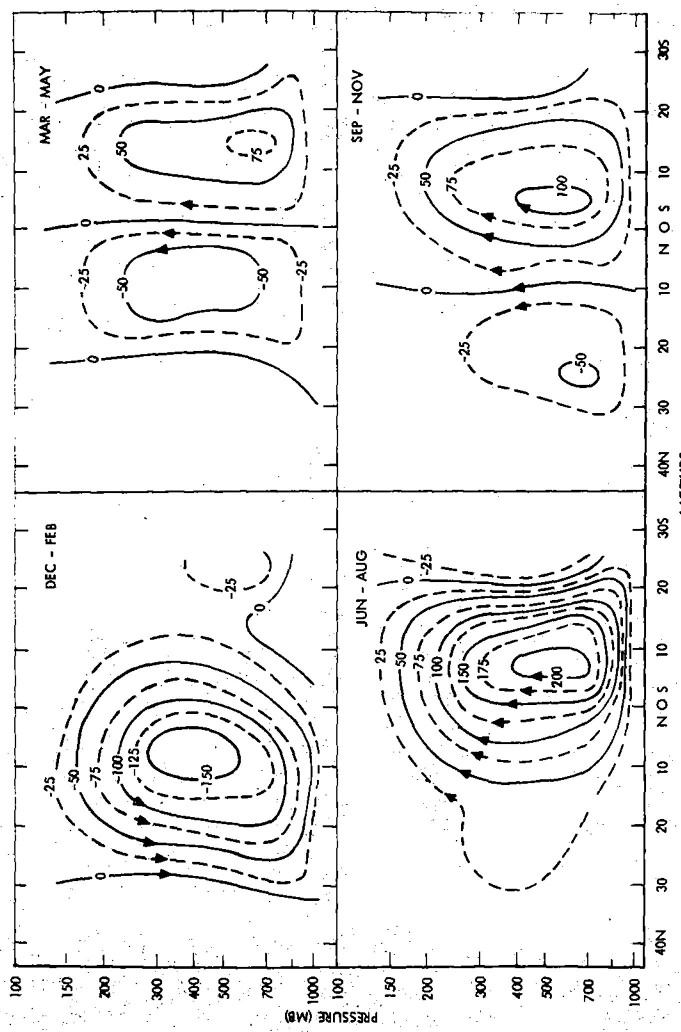

Figure B-9. Streamlines of Mass Flux (10^{12} g/sec)

Space Division
North American Rockwell

There is a considerable amount of meteorological literature pertaining to the growth of symmetric circulations such as the Hadley cells, under various conditions of heating contrast and rotation; most notable is the work of Kuo (1954a, b and many other papers). Stone (1967) has applied some of the reasoning to Jupiter although he favors differential radiation as a driving force (my suggestion here that latent heat release may be as important or more important seems to be original). The cloud photographs also show evidence in Jupiter of eddy-type motions. The horizontal motion pattern can probably best be studied by sequential cloud photography, as has been used to date to determine the rotation period and establish the existence of a westerly jet near Jupiter's equator. Little is known about the motion field above the clouds although it is important in the energy budget there. The horizontal temperature field is also an important part of this question presently unexplored. Correlations between temperature and meridional motion give a measure of the heat transport.

QUESTION 4

Details of the mechanisms by which interchange of kinetic energy takes place between the various scales of motion are required. For example, is momentum transfer down the gradient, as at low latitudes in the troposphere, or up the gradient as just south of the terrestrial jet stream? The profile of zonal velocity and the eddy momentum flux determine this aspect of kinetic energy conversion. Motion determinations must be accurate enough so that correlations between the zonal and meridional components are reliable. Kinetic energy may also be transferred to the upper atmospheres of the outer planets, there to appear as substantially greater velocities. For example, some of the tidal energy, generated by heating of the atmosphere below 50 km, leaks up to the thermosphere. While the tropospheric tidal velocities are fractions of a meter per second, at the 100 km level they reach 100 $msec^{-1}$.

In addition to understanding how each planetary atmosphere works, we should also like to be able to explain the distribution of trace constituents. Some of these, such as methane and ammonia, will be of obvious importance in the atmosphere energy budget. The distribution of ammonia on Jupiter, for example, may be inextricably linked with the circulation through the Hadley cell-type circulations just as water is on earth; in such a case it is very difficult to separate cause and effect. The distribution of other substances such as sodium on earth (which probably originates from the oceans) is governed by the circulation; aerosols also probably fall into this category.

A special class of trace substances are the ions and electrons; we require knowledge of their sources and sinks, their transport by electric fields and atmospheric motions, and their possible acceleration into radiation belt populations. Concomitantly, the magnetic and electric fields involved must be observed and understood. Photoionization is the main source of electron and ion production on earth, but at the substantially greater distances it may be that particle precipitation is of equal or greater importance at high latitudes on the outer planets. The electric fields on earth derive either from the motion of the air through a magnetic field (in the E-region) or from the motion of plasma in the magnetosphere. These fields, then, should be measured for the outer planets. The precipitating particles may be expected to produce auroral emissions and the ionospheric reactions plus the various photochemical chemical processes may be expected to produce airglow. These optical phenomena will provide valuable clues concerning the mechanisms taking place in the upper atmospheres.

Another special class of trace substances are those which may be related to the origin of life. While they may not be directly pertinent to understanding how present atmospheric processes work, they are certainly relevant to the problem of the evolution of the atmosphere and should clearly be included in any atmospheric sampling program.

OBSERVATION REQUIREMENTS, 1975 TO 1990

QUESTION 1. HEAT SOURCES AND SINKS

In the earth's troposphere the important radiative constituents in the IR are H_2O and CO_2. The important phase changes involved are those of H_2O and the factor most controlling the visible light distribution and penetration to the surface is H_2O clouds. In the stratosphere and mesophere, the IR transfer is dependent on CO_2 and O_3 and the UV absorption of O_3 and O_2.

Jupiter

In the Jovian troposphere we might anticipate NH_3, CH_4, and H_2 to be the important IR radiative constituents. (Gillett, et al., 1969). The important phase changes will be those of the NH_3-H_2O cloud system (Lewis, 1969) and will control the visible light distribution. In the Jovian stratosphere the IR transfer is probably dependent on CH_4 and NH_3 and the UV absorption, at least in the region 1450-2200A, mainly on NH_3, and between 1000 and 1450A on CH_4 (McNesby, 1969). There may be other products of photolysis of these substances that are important in the UV. Note that there has even been a suggestion of the presence of atomic oxygen (Moos, et al., 1969).

From the present facts, then, an observational requirement is the concentration of H_2, CH_4, and NH_3 as a function of latitude, longitude, and height. Density and pressure will thereby be specified but computation of the IR transfer requires temperature also.

Below the tropopause, a reasonable goal is to determine the concentrations to within 20 percent. Variations with longitude are not as important as variations with latitude and a goal is a measurement every two degrees of latitude, 20 degrees of longitude, and 5 km of height. A goal for temperature is ±1°K with the same grid, and an areal resolution of $10^4\ km^2$.

Above the tropopause goals are 50 percent for concentration ±5°K for temperature, 2 degrees latitude, 20 degrees longitude, and 10 km height.

Possible experimental approaches are a limb-scanning spectrophotometer for density above the clouds, coupled with selective filters (in the 1700-2200A region) to determine NH_3 and possibly CH_4 (1300-1400A?) from absorption of the Rayleigh scattered light. Temperature could then be obtained directly through integration of density versus altitude.

At and below the cloud or haze tops, it may be reasonable to assume that the CH_4 mixing ratio is constant and use an infrared spectrometer, like that used by Wark and Hilleary (1969), assuming the CO_2 mixing ratio is constant, to determine the temperature profile. Note that the method works also in the presence of clouds and also yields a surface temperature.

In addition, an IR scanning spectrometer such as that discussed by Hanel and Conrath (1969) may enable NH_3 distributions to be obtained in the dark regions.

The distribution of clouds which will govern the deposition pattern of solar energy can best be obtained by imaging with filters (e.g., CH_4 at 8900, Owen and Mason, 1969). It is not yet clear that cloud height can be obtained in this way. The cloud albedo over the range 2000-10,000A is required to 0.05. From the point of view of computing latent heat release, as is the interest here, the rainout from the clouds as well as their vertical distribution is required. Radar scanning at 3 and 10 cm would show up precipitating regions of the clouds, if any, and also give a measure of the rainfall rate; it would also reveal the surface location. Grid sizes required are the same as for temperature and concentration. Imaging with filters on a scale of 1 degree latitude and longitude would be helpful to determine the smaller scale variations in solar heat input. Possible elevated aerosol layers which will influence the scattering and solar energy deposition will also be revealed by the limb scanning experiment.

Saturn

The observational requirements are very similar to those for Jupiter under this heading. The smaller abundance of NH_3, presumably due to the lower temperatures, will probably lead to a different type of heat balance in the region above the tropopause (i.e., NH_3 is not so likely to be involved in the UV absorption). The greater abundance of CH_4 may simply reflect a lower cloud top.

Uranus

The very great abundance of CH_4 observed may again reflect a low cloud top. A basic unknown parameter is the latitudinal scale of the zones and bands. Bands are indicated by the photographs available but resolution

Space Division
North American Rockwell

›r. Hence, measurements like those outlined for Jupiter would be a ep forward. The temperature field may never be subject to analysis the earth. The clouds themselves may be methane rather than ›nia in solution and a variety of filters should be carried for the cloud ng experiments. As well as those specifically directed at absorbing (such as 8900A for CH_4 used by Owen, 1969), there should be filters ıed to the UV and IR at wavelengths where absorption is not antici- (e.g., 3500 ± 200A wide). This would help in a search for clouds ferent levels.

In 1985, the north pole of Uranus and Neptune will be pointing toward ırth and sun (Alexander, 1965). The cloud patterns, then, particularly dark hemisphere, will be of special interest. If these patterns are mined by the solar energy deposit, they should clearly be different in ro hemispheres. If the boundary layer heating is the dominant energy e, the cloud patterns may well change little. Infrared imaging has very successful for the determination of cloud patterns at night in the strial case.

ne

The observation of even more CH_4 than Uranus suggests (to me) an lower cloud altitude, as might be anticipated from the quite weak solar y available to drive the circulation. The question of internal heat es has, however, arisen once again (e.g., Aumann, et al., 1969) being once thought to be settled by Jeffreys. If such sources exist, he prime energy source for the circulation may be heating from and no *a priori* arguments about the clouds may be made. The osition and temperature requirements are the same as those for r under this heading. There is no well documented case for bands ›nes and any information on the distribution of clouds will therefore advance. Cloud photographs with one degree resolution were sug- d for Jupiter as pertinent to the local variations of solar energy input. ame resolution is desirable on Neptune. We do not know whether d structure dominates; the temperature sounding, therefore, should e performed at high spatial resolution, say 200-km squares, but it nly be necessary to do this at, say, 100 points over the disk.

TION 2. GENERATION OF AVAILABLE POTENTIAL ENERGY

The computations require net heating rate (UV, visible, IR, latent elease) throughout the volume together with boundary layer flux; rature is required at the same grid points. They proceed as out- for example, by Lorenz (1967); we have recently carried out a set h computations for the global atmosphere up to 30 km (Newell, et al.,

1970) and have previously presented estimates for the 15-80 km region (Newell, 1963) and the 100 to 10-mb region (Newell and Richards, 1969). As temperature was already specified as a necessary observational requirement under Question 1, there is no additional specification here. Given the cloud distribution and the various radiative fluxes, the radiative heating rate calculations are straightforward. The boundary layer contribution, if any, is quite complex and requires temperature at the surface and in the lower layers of the atmosphere. The most difficult part, perhaps, is the latent heat release effects which require essentially rainfall rate data. On earth, we have had the opportunity to relate rainfall rate data to measured radar backscatter. Signal intensity and Doppler shift are required; the latter may give terminal velocities of the "hydrometeors" and updraft velocities in the clouds but the rainfall rate interpretation will be very difficult.

QUESTION 3. CONVERSION OF AVAILABLE POTENTIAL ENERGY TO KINETIC ENERGY

This portion of a planetary energy cycle involves air motions. It is primarily motions in the lower atmosphere (troposphere and lower stratosphere for earth) that are of importance. Because of the reduction in density with altitude, the kinetic energy density is low in the upper atmosphere and energy transfer from the lower to the upper atmosphere is more important than the reverse process. A detailed knowledge of the motions in the lower atmosphere is therefore required under this heading. The only feasible remote technique at present seems to be to use the clouds as tracers of the motion field. Sequential cloud photography of the same region is required such as could come from a cloud satellite in synchronous orbit. The photographs would preferably be taken with a set of filters to distinguish clouds at different levels as the wind velocity versus altitude is required. The work by Chapman (1969) on the zonal wind component in Jupiter is the only example of the type of information required. For present purposes both wind components are necessary. Chapman's data show that the velocities range up to 100 $msec^{-1}$. For many of the slower speeds an estimate to within 0.5 $msec^{-1}$ is desirable. For a comprehensive general circulation study the velocity pattern should be measured every 2 degrees of latitude and every 10 degrees of longitude. While some longitudes should be sampled simultaneously, it is quite possible that the longitude coverage could be made satisfactorily on different rotations. The frequency of measurement should be once per rotation period. The imaging process needs to produce a very clear end product in order to enable velocity pattern to be derived from displacements. It may well be necessary to use high magnification and examine the patterns in, say, 10-degree grid squares, one at a time. The mean motions resulting (averaged over many rotations) would be used to construct the mean circulation pattern (Figure B-8) and the daily values together with temperature values required at the same place, time, and resolution used to compute heat transports.

In passing, we note that some information on upper atmosphere motions may be derived from Doppler shift of airglow lines (Armstrong, 1968) but at present these lines are not known for the outer planets.

These energy conversions involve essentially the factors $2\Omega \sin\phi$ $[\bar{u}][\bar{v}]$, where $\bar{u}$ and $\bar{v}$ are the time mean zonal and meridional wind components, ϕ is latitude and Ω angular rotation rate, and $[\overline{vT}]\partial T/\partial\phi$ where T is temperature and [ ] represents an average round a latitude circle. The second term represents the conversion from so-called zonal available potential energy to eddy available potential energy. From this latter quantity, the conversion to eddy kinetic energy involves vertical motion (e.g., warm air rising and cold air sinking) in the eddies. The first term represents the direct conversion from zonal available potential energy to zonal kinetic energy. Judging from the photographs showing zonal flow, it is more likely to be the largest loss term for zonal available potential energy. This is fortunate as the vertical motion pattern on an eddy scale is still not properly measured on earth and would be very difficult to estimate on the outer planets by any presently known technique.

The requirements are essentially the same for all four outer planets. But in view of the lack of data presently on the velocity field except for Jupiter, the numerical requirements may differ. For example, much slower speeds would require a smaller absolute uncertainty in the determinations. A fairly good picture can be obtained if a goal is to determine the velocity at a point to within 10 percent of its value.

QUESTION 4. INTERCHANGE OF KINETIC ENERGY

In the terrestrial case kinetic energy converted from available potential energy on the eddy scale is fed back to the larger scale to maintain the mean zonal flow. Estimates of the conversion rate are derived from the quantity $[\overline{u'v'}]\partial[\bar{u}]/\partial\phi$. At middle latitudes, for example, one finds $[\overline{u'v'}]$ positive and $\partial[\bar{u}]/\partial\phi$ also positive equatorwards of the jet stream; hence conversion is into the mean zonal flow. On the outer planets, with their predominantly banded cloud structure, it may well be that the conversion is in the opposite sense and tends to reduce the mean zonal flow. The terms will be available under the requirements for Question 3. The photographs of Jupiter (e.g., Slipher, 1963) show many occasions when eddy structures are present, sometimes even spanning the equator.

In addition to the planetary energy budget, with which Questions 1 to 4 were concerned, there are other items which are part of a complete understanding of the planetary atmospheres. One is the angular momentum budget for which the three-dimensional motion field is required. Specifications have already been made to obtain the pattern of two-dimensional motions. The third dimension must come from the continuity equation. Another item is the atmospheric mass budget; it entails knowledge of the sources, sinks, and transfer of each of the atmospheric constituents. While some of this information may already have been included under Question 1, there are most likely substances of interest other than those directly involved in the radiation budget.

TRACE CONSTITUENTS

We note that the amount of a particular gas present reported by earth-based measurements is very much a function of the technique and wavelength used. For example, Owen (1969) reports an H_2 abundance on Saturn of 190 km atm as measured at 6367A whereas Bless, et al., (1968) report 25 km atm as measured in the 2100-2800A region. Presumably the latter measurement reflects scattering from a higher layer of the atmosphere. We also note that CH_4 abundances increase from Jupiter to Neptune - an effect which could be due to a decrease of cloud top altitude with distance from the sun. Measurements made over cloud-free regions of each planet could sort out these problems. It would seem desirable to search for other trace substances, such as the photolysis products mentioned, which are not necessarily of importance as radiative constituents; this could be done at higher resolution at a relatively few points over the surface - say 20 points. A scan across the whole spatial range 1000-2000A, 2000-10,000A, 1μ-20μ, should be attempted at each point, both looking down and at the limb. The resolution should be good enough to detect single lines ($\lambda/\Delta\lambda \approx 100?$).

Aerosols may be important both in the energy budget, mainly through their reflecting properties, and in the trace constituent budget. A powerful approach for distinguishing molecular and aerosol scattering would seem to be measurement of the wavelength dependence of polarization (Gehrels, et al., 1969). I have not worked through the results of such experiments and so have no feel for its quantitative capability—I would like to know the extent of aerosol haze over the disk on a grid size of about 2 degrees latitude, 20 degrees longitude for the energy computations.)

From the point of view of ionospheric physics, one needs concentrations of substances from which can be ionized, particle influx from the solar wind (if any), and magnetosphere and electron concentration profiles. The latter are a fundamental requirement. The topside profiles could be obtained from a satellite using techniques like those on Alouette I and II. Good areal coverage is required as we have found on earth that electron transport within the ionosphere is an important factor in determining local concentrations. Sampling at a grid of 5 degrees latitude and 20 degrees longitude would be appropriate. Also desirable is the delineation of the magnetic and electric fields within the ionosphere; it is not obvious how

these can be determined remotely but an orbiting satellite within the radiation belt limits would provide data on local fields which could be extrapolated downward to the ionosphere. Some of the physical processes ocurring within the ionosphere may also be monitored by their optical emissions. Auroral emissions will give some evidence about the bombardment processes and some airglow lines (6300A in the terrestrial case) can give information about the dissociative recombination processes. These emission lines should be evident from the detailed scan mentioned above.

A general point about all those observation requirements is that they require data over the disk. As noted, horizontal gradients of temperature and horizontal variability of the wind are important features. It is difficult to see how the spatial coverage required may be obtained from a single flyby; rather orbital missions seem to be desirable.

RELATIVE IMPORTANCE - PROBLEMS

In my opinion the outstanding problem is understanding the energy budget of planetary atmospheres. If we accept Westphal's (1969) recent measurement of a temperature of 300°K deep in the atmosphere of Jupiter, then it is fairly clear that solar radiation is not the dominant factor in the energy budget. I have previously argued (Newell, 1967) that no conceivable greenhouse effect could explain the high temperature of Venus; an identical argument applies to Jupiter, Saturn, and Uranus (if some of their large microwave emission also comes from deep in their atmospheres). For these planets and Venus, then, an internal heat source is required. It may well be ultimately responsible for driving the motions which produce the cloud bands on Jupiter (Peek, 1958), Saturn (Alexander, 1962), and Uranus (Alexander, 1965). While there are many suggestions that gravitational contraction may supply the energy for the outer planets, there have been no such arguments put forward for Venus. It is always satisfying to find a common explanation for such problems. The determination of the horizontal temperature gradient at depths well below the cloud tops is then a first priority measurement.

At the surface itself, the temperature may be determined by an S-band radiometer except in the case of Jupiter where emission from the radiation belts may interfere.

Numerical values of the order of importance of the scientific knowledge and observation requirements are assigned in Tables B-5 and B-6, respectively. We conclude with a series of sketches (Figures B-10 to B-13) showing the value of incomplete attainment of the observation requirements.

Space Division
North American Rockwell

Table B-5. Scientific Knowledge Requirements - Importance

Knowledge Requirement	Importance
Energy Budget: Troposphere	1.0
Stratosphere-mesophere	0.6
Thermosphere	0.2
Momentum Budget: Troposphere	0.7
Stratosphere-mesophere	0.5
Thermosphere	0.1
Mass Budget: Troposphere-substances with phase change	0.95
Troposphere-aerosols	0.85
Mass Budget: Stratosphere-mesosphere	0.4
Mass Budget: Thermosphere	0.25
Ionospheric morphology	0.8
Aurora	0.65
Airglow	0.5

Table B-6. Observation Requirements-Importance

Observation Requirement	Importance
Temperature vs height at different latitudes	1.0
Temperature vs height at different longitudes	0.55
Horizontal wind velocity to cloud top level	0.95
Horizontal wind velocity above cloud top	0.4
Composition atmosphere	0.85
Composition clouds	0.8
Composition haze - if any	0.5
Surface temperature pattern	0.75
Electron concentration profiles - topside sounder	0.65
Auroral spectra	0.45
Airglow spectra	0.35
Magnetic fields	0.6

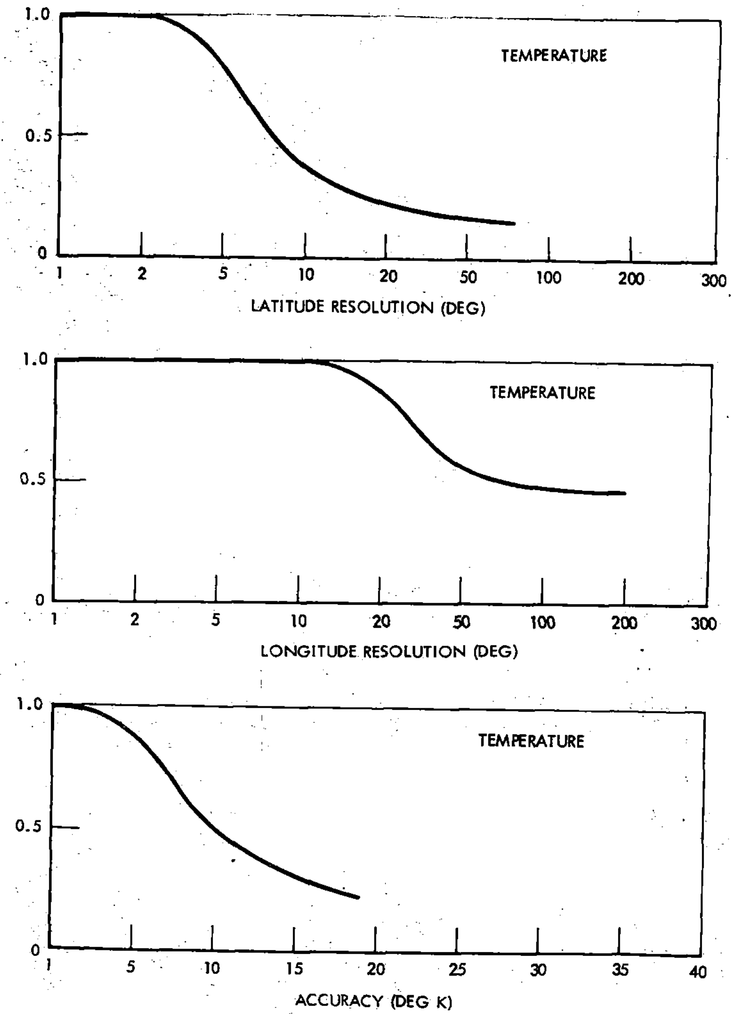

Figure B-10. Worth Curves for Temperature Observations

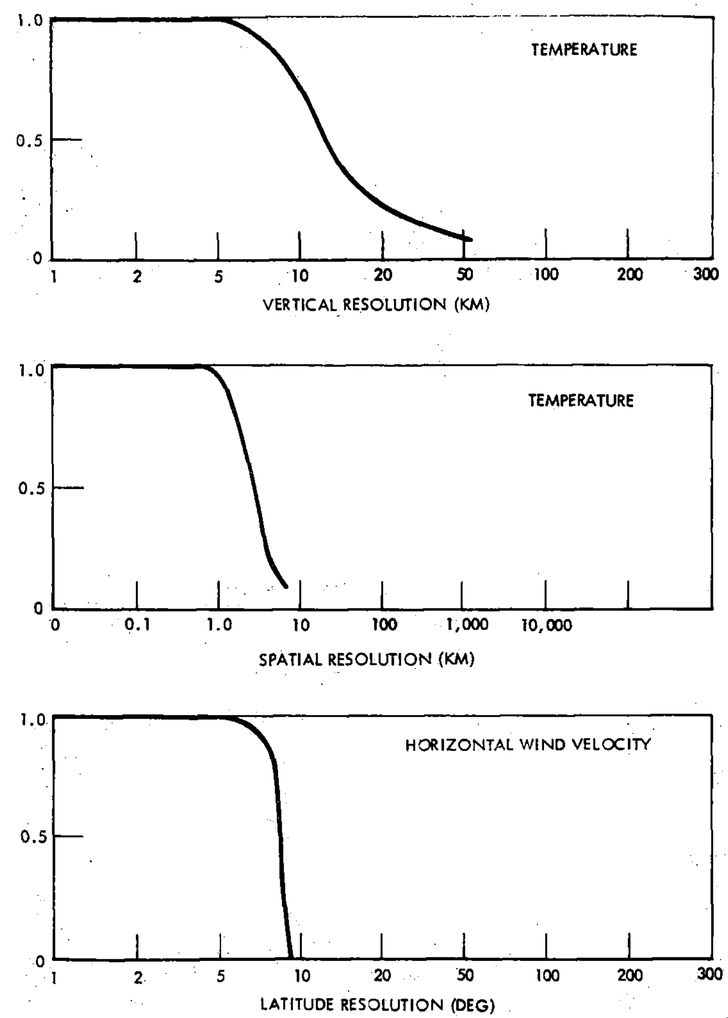

Figure B-11. Worth Curves for Temperature and Wind Measurements

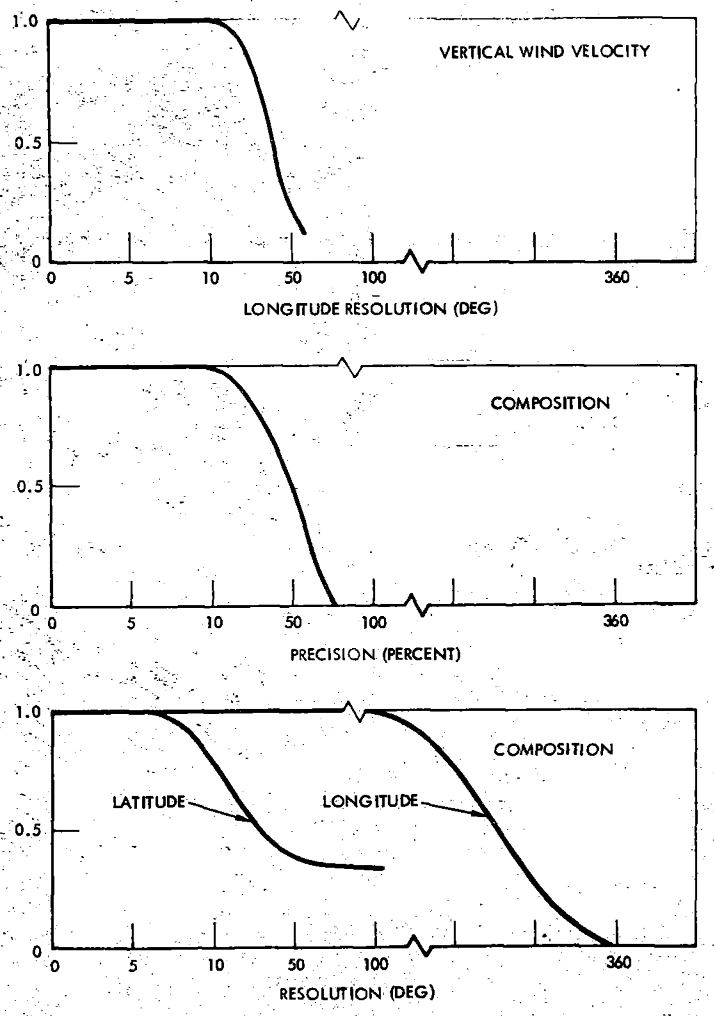

Figure B-12. Worth Curves for Wind and Composition Measurements

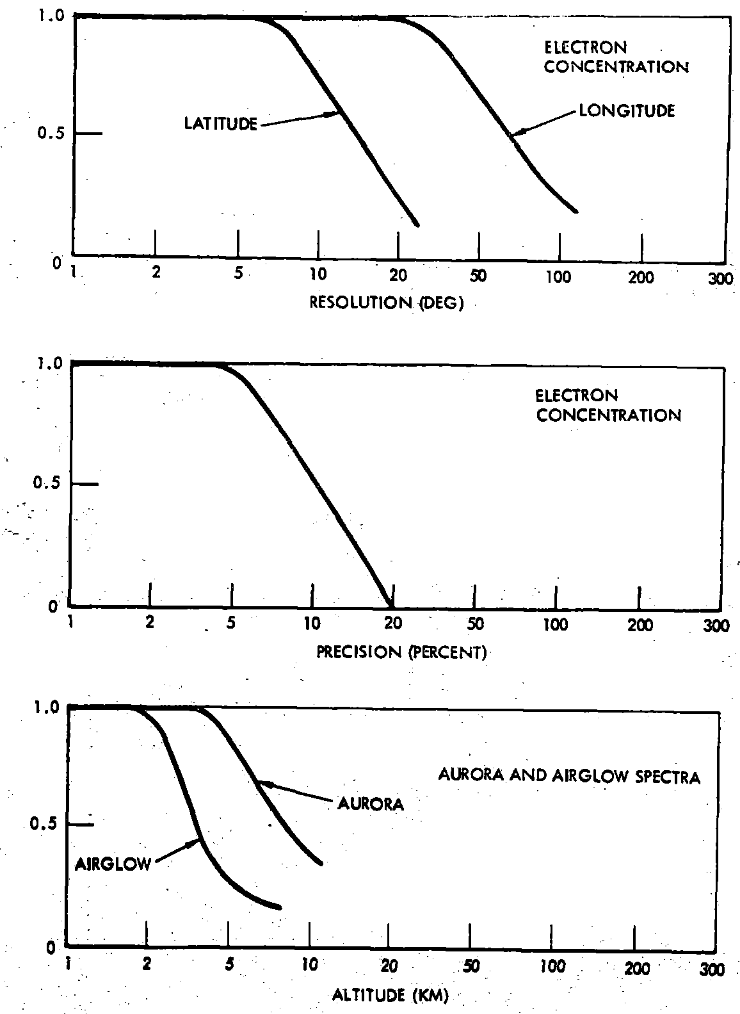

Figure B-13. Worth Curves for Ionospheric Observations

APPENDIX C. OBSERVATION REQUIREMENTS TABULATIONS

This appendix presents the planetary observation requirements, appropriate to remote sensing, in the form of the printed output of the SERA-1 computer program. The arrangement and interpretation of the output information are discussed in Section 3.3. The observation requirements are described qualitatively in greater detail in Section 5.0. The computer program description is contained in Appendix D.

Tables C-1, C-2, and C-3 show the relevant associations of goals, knowledge requirements, observation objectives, and observable properties. These tables are the same as Tables 4, 7, and 9 of the main report, and are repeated here for completeness of the tabulation. Table C-4 is a listing of the library of titles of goals, knowledge requirements, observation objectives, observable properties, observation techniques, observation parameters, planets, and worth functional forms. Descriptions of sub-objectives and sub-observables are added to provide more detail than the basic titles.

Table C-5 is a condensed guide to the observation requirements. It indicates all combinations of goal, knowledge requirement, observation objective, observable property, observation type, and planet to which each observation requirement is relevant. The worth w_k of each observation objective, and the worth $w_{j\ell}$ of each observable property-planet combination in support of each observation objective, are indicated. If either w_k or $w_{j\ell}$ is less than 0.20, *no results* are presented. To avoid unnecessary repetition, only one case is displayed in detail for each combination indicated in Table C-5. If any of the observation requirements change quantitatively, a new combination is shown. The observation sub-objective and sub-observable descriptions are more specific than the objective and observable titles in the computer program library.

Table C-6 contains the detailed observation requirements. This table is divided into four main sections as follows:

(i) Observations limited to the inner planets (nonimaging only)

(ii) Observations common to inner and outer planets (nonimaging only)

(iii) Nonimaging observations limited to the outer planets

(iv) Imaging observations limited to the outer planets

APPENDIX D. COMPUTER PROGRAM DESCRIPTION

A program or series of programs for the IBM S/360, Model 65, digital computer is required for the storage, retrieval, and analysis of data pertaining to planetary observation requirements, remote sensor performance requirements, sensor scaling laws, and sensor support requirements. The overall program, called Space Experiment Requirements Analysis (SERA), will be developed in a progression of modular steps through Phases 1 and 2, and possibly Phase 3, of the study. Only the first module (SERA-1), dealing with observation objectives and requirements, is to be developed and used in Phase 1.

OUTLINE OF ANALYSIS

SERA-1 is an input/output program intended for automated retrieval and documentation of quantitative and descriptive planetary observation requirements data. It is anticipated that SERA-1 will later be combined with routines to correlate these data with sensor capability and support requirements information (see Figure D-1).

The input data to SERA-1 consists of:

1. Program control parameters which select input and output options and establish which SERA modules are to be called. If SERA-1 alone is used, the only meaningful option is to use it to read and print data.

2. A library of identification numbers and titles of planetary exploration goals, knowledge requirements, observation objectives, planets, observable properties, observation types, observation parameters, and functional form types. These terms are defined in Sections 4 and 5, and the present contents of the library are presented in Table B-3.

3. Data entered for keypunching on the Planetary Observation Requirements Data Sheet (ORDS), Figure D-2 (page D-39).

Let w_{mk} be the worth (i.e., the value to science and technology) of complete achievement of the k th observation objective, insofar as that objective is related to the m th combination of goal and knowledge requirement ($0 < w_{mk} < 1$). w_{mk} is entered on the ORDS in columns 13-16, line 1.

BIBLIOGRAPHY

Alexander, A.F.O'D., 1962: The Planet Saturn, Faber and Faber, London.

Alexander, A.F.O'D., 1965: The Planet Uranus, Faber and Faber, London.

Armstrong, E.B., 1968: Planet. and Space Sci., 16, 211.

Aumann, H.H., and C.M. Gillespie, Jr., 1969: Ap. J., 157, L69.

Bless, R.C., A.D. Code and D.J. Taylor, 1968: Ap. J., 154, 1151.

Chapman, C.R., 1969: J. Atmos. Sci., 26, 986.

Gehrels, T., B.M. Herman and T. Owen, 1969: Astron. J., 74, 190.

Gillett, F.C., F.J. Low and W.A. Stein, 1969: Ap. J., 157, 925.

Hanel, R. and B. Conrath, 1969: Science, 165, 1260.

Kuo, H.-L., 1954a: J. Met., 11, 399.

Kuo, H.-L., 1954b: Final Rept., General Circulations Project, Dept. of Meteorology, M.I.T., p. 479.

Kuhn, W.R. and J. London, 1969: J. Atmos. Sci., 26, 189.

Lagos, C.P., 1967: On the dynamics of the thermosphere. Rept. No. 20, M.I.T., Dept. of Meteorology, 134 pp.

Lewis, J.S., 1969: Icarus, 10, 365.

Lorenz, E.N., 1967: The Nature and Theory of the General Circulation of the Atmosphere, WMO. Publ. 218.

McNesby, J.R., 1969: J. Atmos. Sci., 26, 594.

Moos, H.W., W.G. Fastie and M. Bottema, 1969: Ap. J., 155, 887.

Murgatroyd, R.J. and R.M. Goody, 1958: Q. J. Roy. Meteor. Soc., 84, 225.

Mahoney, J., 1966: A study of energy sources for the thermosphere, Rept. No. 17, MIT Dept. of Meteorology, 218 pp.

Newell, R.E., 1963: J. Atmos. Sci., 20, 213.

Newell, R.E., 1967: Icarus, 7, 114.

Newell, R.E., D.G. Vincent and J.W. Kidson, 1969: Tellus (in press).

Newell, R.E. and M.E. Richards, 1969: Q. J. R. Meteor. Soc., 95, 310.

Newell, R.E., D.G. Vincent, T.G. Dopplick, D. Ferruzza, and J.W. Kidson, The energy balance of the global atmosphere, paper presented at the Conference on the Global Circulation of the Atmosphere, London, August 1969, Proceedings to be published by the Royal Meteorological Society.

Owen, T., 1969: Icarus, 10, 355.

Owen, T. and H.P. Mason, 1969: J. Atmos. Sci., 26, 870.

Peek, B.M., 1958: The Planet Jupiter, Faber and Faber, London.

Rodgers, C.D., 1967: The radiative heat budget of the troposphere and lower stratosphere. Rept. No. A2, MIT Dept. of Meteorology. 99 pp.

Slipher, E.C., 1964: A photographic study of the brighter planets. Lowell Observatory and National Geographic Society.

Stone, P.H., 1967: J. Atmos. Sci., 24, 642.

Wark, D.Q. and D.T. Hilleary, 1969: Science, 165, 1258.

Westphal, J.A., 1969: Ap. J. 157, L63.